The Thesis Committee for Eduardo Javier Meneses-Scherrer
Certifies that this is the approved version of the following thesis:

Lessons Learned in the Eagle Ford Play and Applicability to Mexico

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor: ______________________________
Scott W. Tinker

Co-Supervisor: ______________________________
Gürcan Gülen

____
Ursula Hammes

Lessons Learned in the Eagle Ford Play and Applicability to Mexico

by

Eduardo Javier Meneses-Scherrer, B.S.

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Dedication

To my parents, Dorina and Javier, for their support and encouragement throughout my academic accomplishments.

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Abstract

Lessons Learned in the Eagle Ford Play and Applicability to Mexico

Eduardo Javier Meneses-Scherrer, M.A.

The University of Texas at Austin, 2015

Supervisor: Scott W. Tinker

Co-Supervisor: Gürcan Gülen

Mexico's oil and gas production decline from conventional reservoirs calls for the assessment of their Late Cenomanian-Turonian shale resources. However, a geological screening of the Texas Gulf coast and east and northeast Mexico indicates that their distinct paleogeographic and tectonic development preclude a straightforward correlation between the Upper Cretaceous Eagle Ford Group of Texas and equivalent formations in Mexico. In Texas, east of the Frio River Line, extensional tectonics prevailed during the Mesozoic-Cenozoic; while in Mexico compressional tectonics influenced sedimentation from the late Cenomanian through the Eocene. Late Cenomanian compression led to paleobathymetry variations that may have influenced the lithology, distribution, and thickness of the lower organic-rich interval of the Eagle Ford Group, as well as the uplift of a western landmass that was a source of detrital argillaceous sediments. Laramide orogeny produced the exhumation of the late Cenomanian-Turonian section in most of the eastern part of Mexico, and its burial in foreland basins below Cenozoic sediments with contrasting thickness. Therefore, uplift and loading burial impacted critical depth-dependent factors such as thermal maturation, pore pressure, and viscosity. Hence, in east and northeast Mexico four

areas have geological and geotechnical characteristics to be potential sweet spots in the Eagle Ford trend. The areas are the Sabinas Coal Basin, the western part of the Burgos Basin, the southwestern part of the Maverick Basin, and the southwestern part of the Tampico-Misantla Basin. Each area may be an opportunity to ensure Mexico´s energy mix and offset the declining production; nevertheless, these areas present significant technical, operational, and public challenges such as water shortage or mismanagement, insufficient road and pipeline infrastructure, and the ability to deal with people with strong cultures and social roots. Once the geologic and engineering data extracted from the appraisal wells permit the understanding of the economic potential of the sweet spots, supply chains may develop around a Northeastern Hub embracing the Burgos, Maverick, and Sabinas Coal Basins, and an Eastern Hub, including the Tampico-Misantla Basin. High-quality project management and decision-making process based on economic and scientific facts may permit a fruitful learning curve.

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Chapter 1: Introduction

BACKGROUND

The United States is home to numerous shale oil and shale gas sedimentary basins that span across states like North Dakota, Pennsylvania, Texas, Colorado, Pennsylvania, and Louisiana (Figure 1). In 2013, the U.S. Energy Information Administration (EIA)[1] estimated that, among 41 countries, the U.S. holds the second and fourth largest technically recoverable shale oil and shale gas resources in the world with approximately 58 billion barrels (Bbbl) and 665 trillion cubic feet (Tcf), respectively. It is important to note, however, that the resource estimates outside the U.S. are more speculative given the limited amount of drilling and production that have taken place in countries such as China and Argentina. In 2014, shale gas and natural gas from tight oil plays in the U.S. made up 50% of the total dry natural gas production (EIA, 2015a).

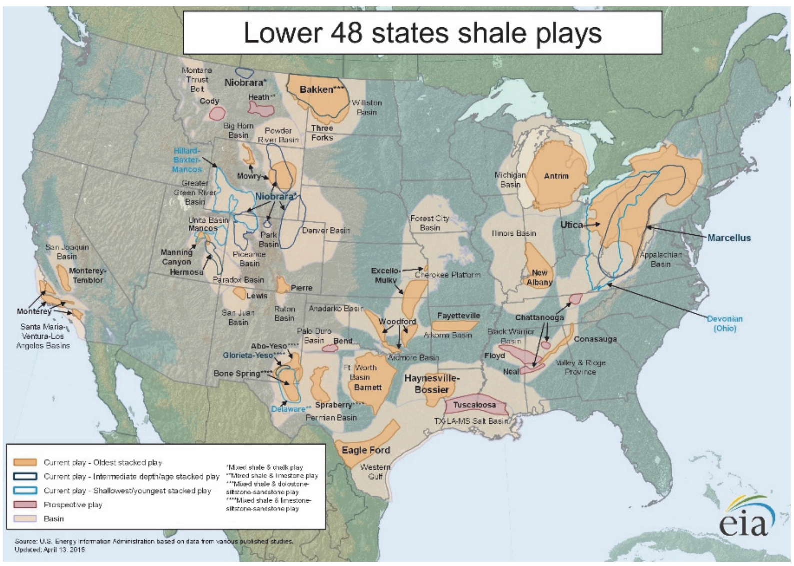

Figure 1: Shale gas and oil plays in the U.S., lower 48 States (EIA, 2015b).

[1]This study was done by a consultancy, Advanced Resources International (ARI), based on the available geologic data. In many cases, data has been limited since there are few or no wells drilled. As such, the estimates can be considered to have a wide range of uncertainty around them. Many basins were excluded owing to lack of data.

The Eagle Ford shale is one of the largest shale gas producing plays although operators have primarily focused on parts of the Eagle Ford that produces more liquids and oil, making the play the largest shale oil producer in the U.S. (EIA, 2015b). As of January 2015, the Eagle Ford shale was producing 4.9 billion cubic feet per day (Bcfd), and 1.6 million barrels per day (MMbpd), 33% and 35% increases respectively for natural gas and oil as compared to January of 2014 (EIA, 2015b) (Figures 2 and 3). The oil production gains led the U.S. to increase annual crude oil production 74% from 2008 to 2014, and consequently were a reason the U.S. imports of crude oil dropped 29% in the same period (EIA, 2015c).

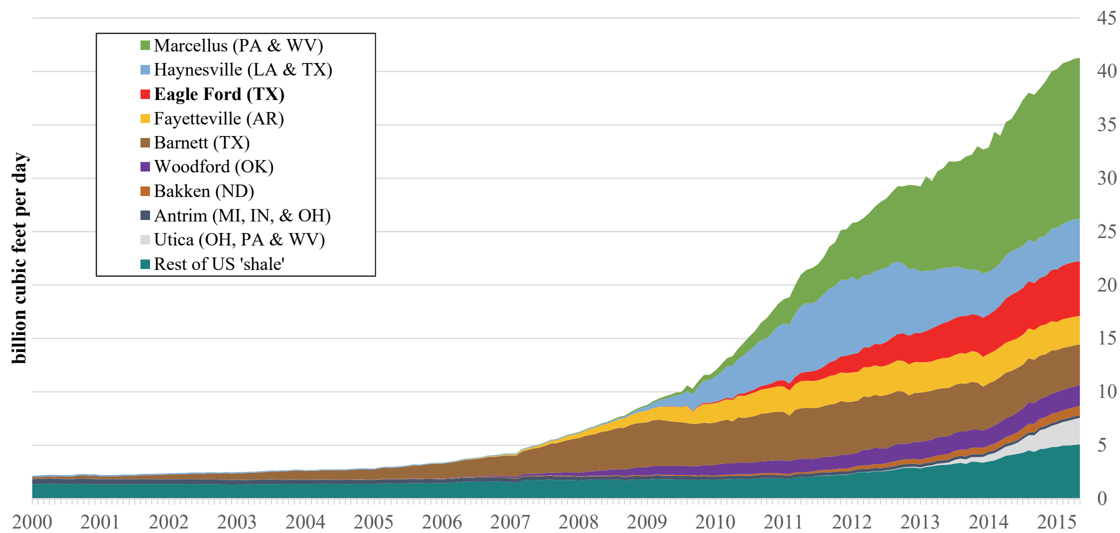

Figure 2: U.S. dry shale gas production by play from January 2000 to May 2015 (data from EIA, 2015b).

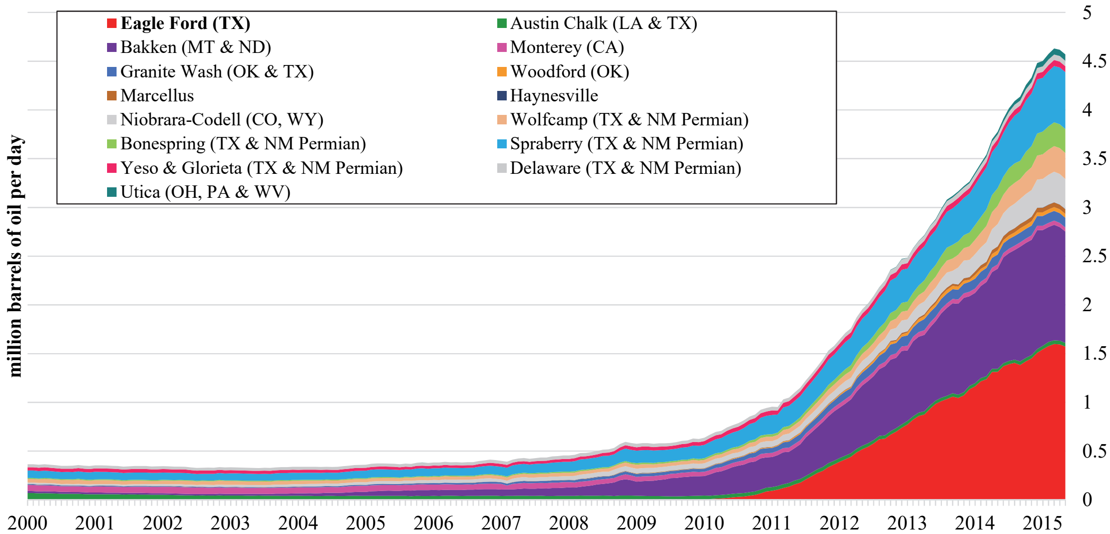

Figure 3: U.S. tight oil production – selected plays from January 2000 to May 2015 (data from EIA, 2015b).

The global economic impact of shale resources could be enormous since the EIA (2013) estimated that in the top 41 countries, the total volume of technically recoverable shale gas and oil resources are around 7,299 Tcf and 345 Bbbl, respectively. However, it is important to acknowledge that only a relatively small percentage of technically recoverable resources can be converted to economically recoverable resources, and that proving reserves out of the economic portion will depend on the ability of the industry to drill a large number of wells and complete them via hydraulic fracturing. This supply chain is not readily available anywhere in the world (outside the U.S.), certainly not at the scale that allowed drilling of more than 30,000 wells a year in the U.S. Without such high-intensity and fast-paced drilling, it is not possible to reach and sustain significant levels of production. It is equally important to realize that the industry cannot develop this supply chain and drill at the necessary pace and intensity unless the resource owners create legal and regulatory frameworks that are supportive of such developments.

In 2013, the EIA ranked Mexico 6th with 545 Tcf and 8th with 13.2 Bbbl in technically recoverable shale gas and oil resources, respectively. According to EIA (2013), these resources are distributed in Upper Jurassic and Upper Cretaceous marine deposits in the Chihuahua, Burgos, Sabinas, Tampico-Misantla, and Veracruz Basins (Figure 4).

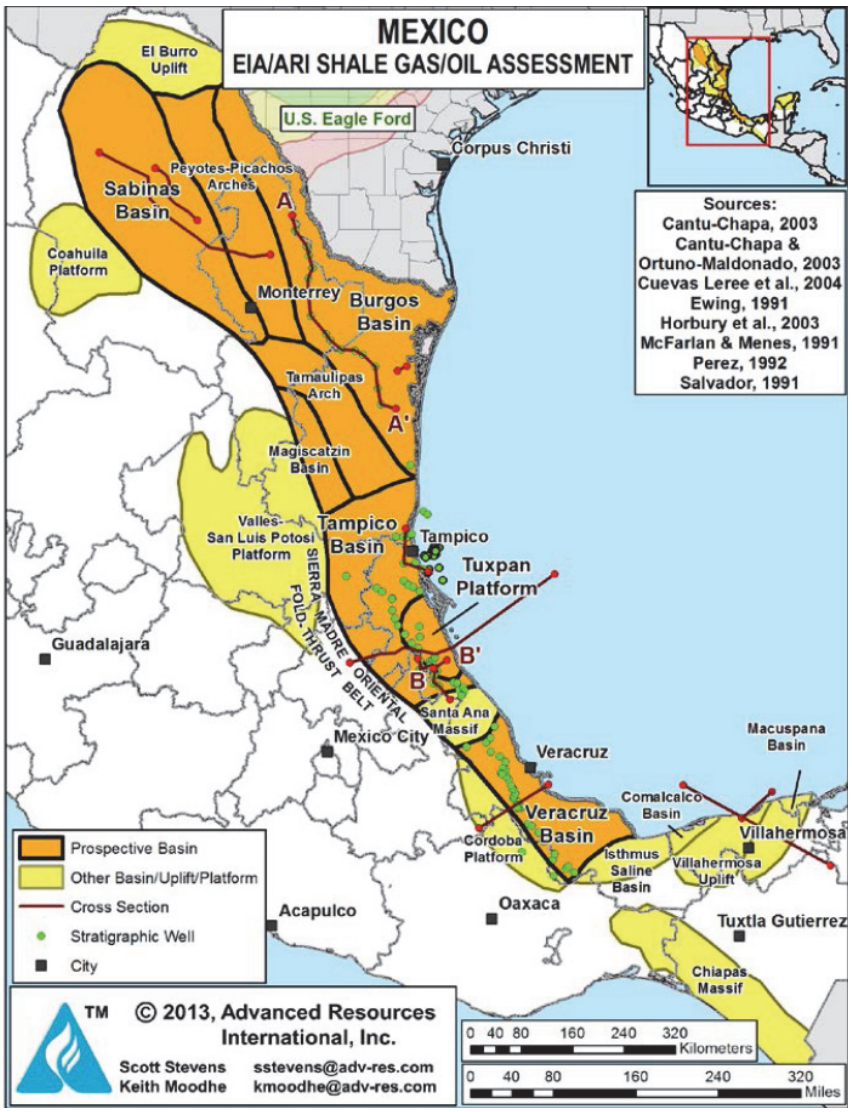

Figure 4: Mexican Basins with Upper Jurassic and Upper Cretaceous shale oil and gas potential (EIA, 2013).

Petróleos Mexicanos (PEMEX) began to explore for shale resources in the Eagle Ford at the beginning of 2010. Through 2014, it drilled eight wells, out of which six were completed at the southwestern end of the Maverick Basin in order to test the extension of the three windows producing in the Texas counterpart (Escalera Alcocer, 2012a) (Figure 5). Only two wells have been drilled beyond the limits of the Maverick Basin. These wells were completed in the northeastern part of the Sabinas Coal Basin (Percutor-1) and in the Burgos Basin (Durian-1); the National Hydrocarbon Commission (CNH) (2015) reported both wells as producer of dry gas.

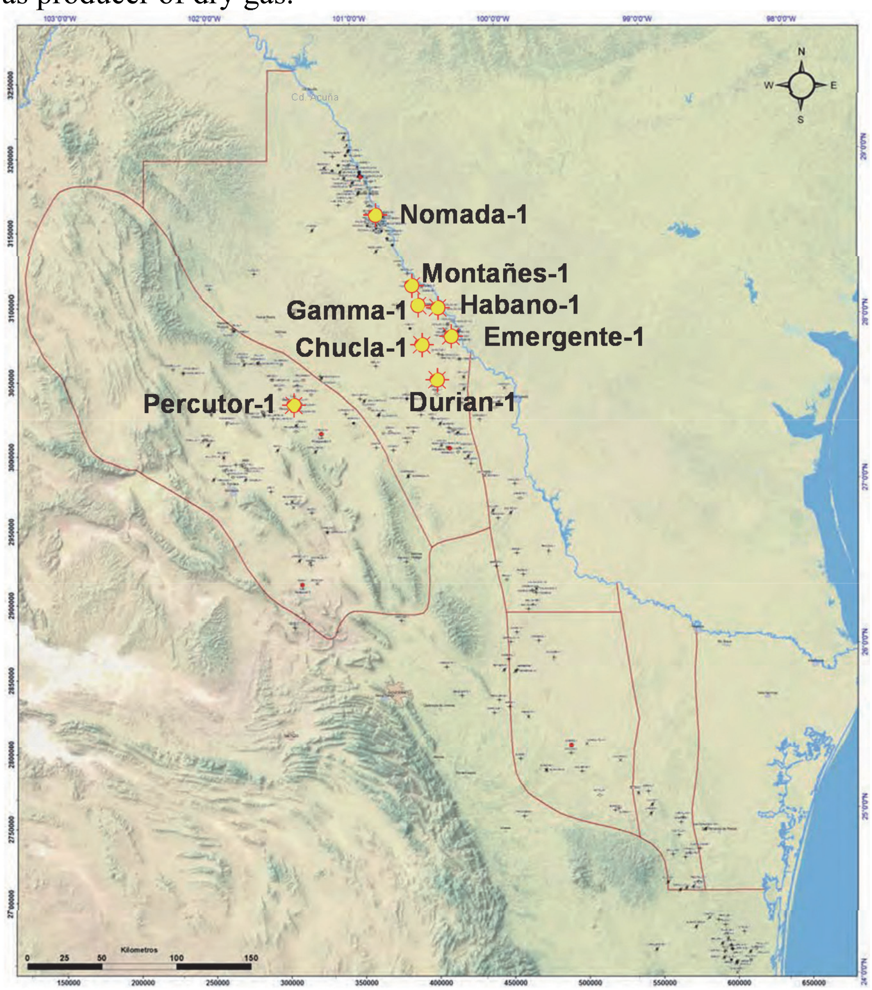

Figure 5: Location of PEMEX´s exploratory wells with the target in the Eagle Ford Group in Mexico (PEMEX, 2015a).

Mexico´s shale gas and oil potential is an opportunity to ensure its future energy mix and offset the declining production of its major fields along with the expected development of new conventional plays, primarily offshore. The economic impact of shale gas and oil development in Mexico could be significant if the players are able to capture the experience, best practices, and scientific knowledge already acquired in Texas, and apply them wisely to the geological and geographical characteristics of the Mexican basins. Like the rest of the world, the legal and regulatory framework should allow for risk-taking companies to develop the required logistics chain and drill wells.

OBJECTIVE AND APPROACH

The purpose of this work is to investigate how the lessons learned in the Eagle Ford play in Texas could be applied to manage the exploration and production process of its geological extension in Mexico, where the appraisal of its potential is in an early phase. To achieve this goal, firstly the major issues that call for the development of a shale gas and oil industry in Mexico are discussed. Following, the geological framework of the Eagle Ford Group in Texas and equivalent formations in Mexico are presented, as a first and preliminary approach to a reasonable applicability of the geological knowledge and experience gained in Texas to the Mexican basins. This geological framework provides some critical information to predict if the key geological conditions and parameters of the Eagle Ford in Texas can be extrapolated into the Mexican basins. Finally, with a geological understanding in mind, the strategic factors that led to the rapid emergence of the Eagle Ford play in the U.S. are examined, in order to identify the main gaps, uncertainties, and challenges that Mexico must overcome to replicate the U.S. success.

STUDY AREA

In Texas, the Eagle Ford Group extends from northeastern Texas to the Rio Grande. In Mexico, the Upper Cretaceous formations equivalent to the Eagle Ford are widely distributed in the northern, central, and southern parts of the country; however, for the purpose of this study, only the formations of northeast and east Mexico are analyzed. These formations were deposited in the Sabinas, Burgos, and Tampico-Misantla Basins and the Mexican Maverick Basin.

Chapter 2: Major Issues that Call for the Development of a Shale Gas and Oil Industry in Mexico

The Constitutional Convention of 1917 established the legal basis on which the Mexican oil industry was nationalized in 1938 by President Lázaro Cárdenas: Article 27 of the Mexican Constitution. This article referred to the property rights in Mexico and the Nation´s right to all substances and minerals under its land. For this reason, Rouaix (1945) states that the Conveners considered it as the most important Article of the Constitution; among the most prominent delegates were individuals who led the Mexican Revolution (1910-1921) against the "old regime" represented by Porfirio Díaz. During his long dictatorship (1876-1911), Díaz issued three Mineral Laws (1884, 1892, and 1901) to abolish this national right that Mexico had at the moment of its independence (1821), due to a legacy from the Spanish Crown (Rouaix, 1945; Labastida, 1990).

The end of the revolutionary upheaval, the aftermath of WWI, the 1929 Great Depression, and the outbreak of WWII were all periods of strong political controversies between the Mexican government and the companies that refused to accept the nationalization of the freehold rights to the subsoil acquired under Díaz's dictatorship (Labastida, 1990; Meyer, 2009). Finally in 1943, the U.S. companies accepted the compensation deal negotiated between the Mexican government and the U.S. State Department (Alemán Valdés, 1976; Meyer, 2009;); but the settlement with the British companies was not reached until 1947 (Bermúdez, 1976; Meyer, 1992). Under these circumstances, PEMEX became the only integrated company and the sole producer of oil, gas, and refined products in Mexico. Rodríguez Aguilar (1950) states that, in 1938, PEMEX had no more than ten specialists in exploration (geologists, geophysics, and paleontologists) and that by the beginning of 1950 this number increased to more than one hundred. Thus, PEMEX emerged as a pioneer of the NOCs, inspiring in some aspects the nationalizations that were subsequently implemented in other parts of the world.

During the first four decades after nationalization, PEMEX was an example of successful performance and was gradually meeting the energy needs of the country. Most of the oil and gas provinces of Mexico were discovered by PEMEX in the period of 1945-1976 (Figure 6).

THE REFORMS OF THE MEXICAN OIL INDUSTRY (1941-2013)

The history of PEMEX´s success was not exempt of lean times during which the company had to adapt its norms to the "actual conditions within which it operated" (Morales, 1992; Meneses de Gyves, 1999). Thus, two important constitutional acts about Article 27 are found in the Mexican Congressional Record (Diario Oficial de la Federacion 1941 and 1958). These acts were signed under Presidents Manuel Ávila Camacho and Miguel Alemán, in 1941 and 1958, respectively. The first act was signed during WWII; the second act was signed when the successful industrial development of Mexico increased the domestic demand for oil (Bermúdez, 1960 in Morales, 1992). The 1941 act stated the possibility that the Nation carry out the exploration and exploitation of petroleum "through contracts with private individuals or with companies in which the major share of capital was from government and the rest might be national or foreign partners." The 1958 act abolished the terms of the first one, but permitted PEMEX to grant service contracts to private companies "in order to carry out its required activities." This act considered that remuneration in such contracts "must be paid only with money" (i.e., not in kind via oil). Amid these constitutional acts, in 1950 the U.S. lent Mexico 150 million dollars for the development of its petroleum industry (Alemán Valdés, 1977; Downes 1983).

In spite of the imprecise writing and contradictory ideas, these two acts were the legal basis of five important contracts signed by PEMEX with private companies between 1949 and 1951 (Alemán Valdés, 1977). The contracts granted ten to fifteen years for exploration and drilling activities to Compañía Independiente Mexicano–Americana (CIMA) (two contracts), Edwin W. Pauley, Sharmex, and Isthmus Development (Morales, 1992). Thus, from 1947 to 1958, 180 exploratory wells out of 764 were drilled by private companies (Morales, 1992). According to Meneses de Gyves (1983) two important contracts were named: the "Tierra Sumergida" and the "Tierra Firme." The "Tierra Sumergida" contract embraced 2,000 km^2 extending offshore from southeastern Veracruz into Ciudad del Carmen, Campeche. The second contract covered onshore areas of the States of Campeche, Tabasco, Veracruz, and Nuevo Leon. With the "Tierra Sumergida" contract, CIMA carried out seismic reflection surveys and mapped three structures offshore Veracruz and Tabasco (Tortuguero, Rabon Grande, and Santa Ana) which became the first offshore discoveries in Mexico. In 1961, CIMA announced the discovery of the Santa Ana field that "could add in excess of 30% to the known reserves of Mexico" and considered that the results in Tortuguero and Rabon Grande were "partly successful and generally disappointing" (Narvarte, 1961, 1962). By 1963, the Santa Ana field produced 9,570 BOPD after the drilling and completion of 53 development wells (García Rojas, 1963). With the "Tierra Firme" contract, CIMA mapped eight structures in Tabasco and Veracruz and in 1951 drilled the Macuiltepec-1 and Macuiltepec-2 wells, in the eastern part of the area that later became the Mesozoic Chiapas-Tabasco Province of southeast Mexico, discovered by PEMEX in 1972 (Meneses de Gyves, 1983). With these wells, CIMA aimed to reach deeper horizons; however, the first well had mechanical problems and the second well only reached 3,000 m in depth (Meneses de Gyves, 1983). As the private companies worked in southeast Mexico, PEMEX continued exploration activities and found several important fields in a row in this part of the country (Figure 6). In 1965, when the term of the contracts ended and during the presidency of Díaz Ordaz, PEMEX decided not to extend the contracts and paid reimbursements to the companies through a deal at the beginning of 1970 (Alemán Valdés, 1977; Meneses de Gyves, 1983; Meyer, 2009).

PEMEX´s exploratory efforts of the 1950s and 1960s found its crowning moment with the discoveries of the giant and super-giant fields in Mesozoic rocks of Chiapas-Tabasco and offshore Campeche, in 1972 and 1976, respectively (Meneses de Gyves, 1983) (Figure 6). These discoveries enabled the country to move from net importer to net exporter and became a key player in the international oil market. However, the richness of these fields led Mexico´s economy to depend heavily on the fiscal contribution of their huge production in such a way that PEMEX has been the single largest source of the Federal Government income (33.2% in 1995, 37.3% in 2005, and 34.6% in 2014; CEFP, 2012; Jardón, 2013; Hernández, 2013; CNNExpansión, 2015) (Figure 7). Thus, PEMEX continuously increased production reaching 3,383 thousand barrels per day (Mbpd) in 2004. Since then, the dominance of a few but very large fields in Mexico´s oil production in combination with fiscal constraints to invest in maintaining production levels from declining fields, exploring for new fields, and investing in technologies and human capital, triggered an economic crisis when Cantarell production began to decline.

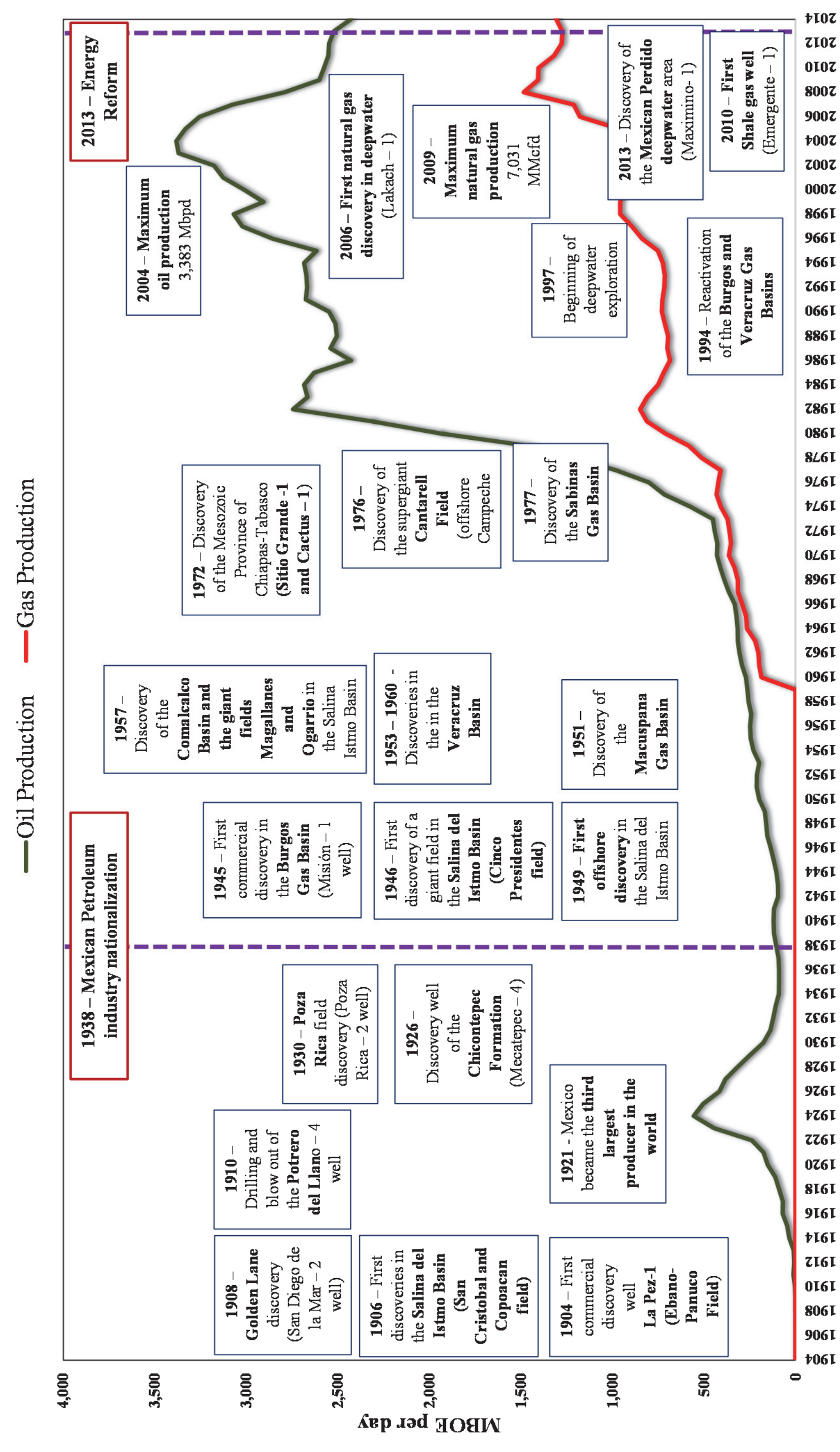

Figure 6: Exploratory milestones and oil and gas production in Mexico from 1904 to 2014 (modified from Escalera Alcocer, 2012b; with data from DeGolyer, 1952, García Rojas, 1962, and Meneses de Gyves, 1999).

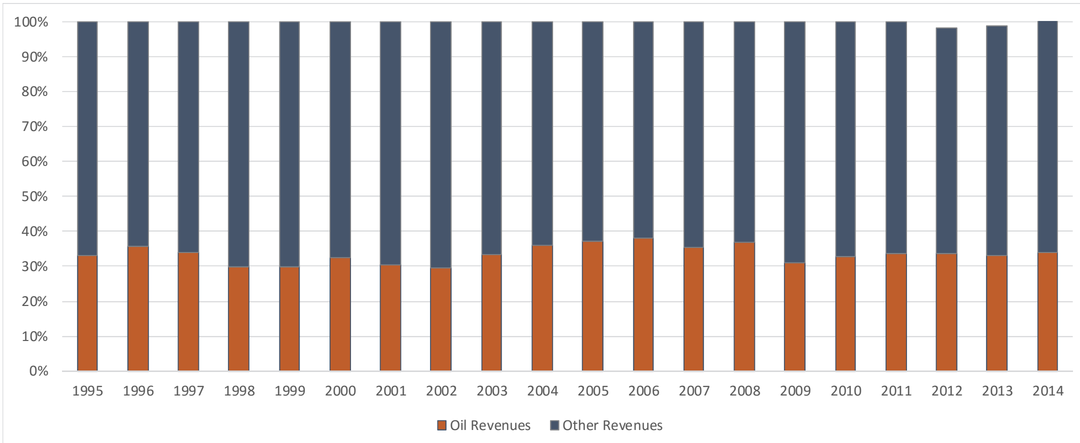

Figure 7: Dependence of Federal Government on oil revenues 1995-2014 (% of budget revenues) (CEFP, 2012; Jardón, 2013; Hernández, 2013; CNNExpansión, 2015).

Besides the rapid oil and gas production decline of the main fields, PEMEX faces other crucial challenges, such as the need to fulfill a growing domestic natural gas demand, the deepwater exploration and production in the Gulf of Mexico, and the assessment of its unconventional resources. These challenges have led the Mexican government to propose three bills in the last twelve years that have required Constitutional amendments. The first amendment was made in 2003 with the purpose of supporting the development, production, infrastructure, and maintenance of non-associated gas fields in the Burgos and Sabinas Basins through "Multiple Services Contracts." These contracts granted to private companies the exploration and production of some blocks of these two basins with remuneration paid only with money and with the Constitutional prohibition of granting concessions. By 2010, the gas production in these areas was below PEMEX's expectations, and the production costs were higher than the import costs (Rodríguez Padilla, 2010). The second amendment was made in 2008 and included the possibility of private companies transporting, storing, and distributing natural gas, refined and petrochemical products. Furthermore, it created the CNH to regulate and supervise the exploration and production of hydrocarbons in Mexico.

Given the historical and cultural roots on which the Mexican petroleum industry has emerged, the two amendments led to a vociferous debate in Mexico´s society about the future of the industry. In December 2013, the most radical reform of the Mexican energy sector since the creation of Article 27 in 1917 was approved by the Congress (two-thirds in both the House of Representatives and the Senate). The reform drastically changed the Mexican oil industry. The changes in Articles 25, 27, and 28, and 21 transitory articles of the Mexican Constitution provide for the authorization of investments from private companies, both domestic and foreign, throughout the value chain, from upstream to downstream. These changes have been accompanied by an intense media campaign by the government, in which high benefits for the population are announced in the short-term due to the approval of the "Energy Reform", such as low future rates of electricity and gasoline. The new law established the following main principles:

1. CNH is responsible for assigning exploration and production contracts either to PEMEX or private companies, following competitive bidding rounds, the common process around the world. The CNH provides technical advisory to the Department of Energy (SENER) and is responsible for concentrating geological and operations information. In addition, this agency is in charge of the technical administration of assignments and contracts; the supervision of extraction plans that maximize productivity in the field, and the regulation of exploration and production.
2. Two new agencies were created. The ASEA (Environmental and Industrial Safety Agency) is responsible for the safety and environmental compliance. CENAGAS

(National Center of Natural Gas Control) will manage the system for gas distribution and storage (Ribando Seelke et al. 2015).

3. Four types of contractual models between the State and private companies were created: "service contracts (companies are paid for activities done on behalf of the state), profit-sharing contracts, production sharing contracts, and licenses (enabling a company to obtain ownership of the oil or gas at the wellhead after it has paid taxes)" (Ribando Seelke et al. 2015).

4. The new law does not allow the State to grant concessions, nor grant ownership of the hydrocarbons to private investors. However, as Ribando Seelke et al. (2015) point out "it allows companies to take ownership of those resources once they are extracted and to book reserves for accounting purposes."

5. PEMEX is a "productive state enterprise" with technical, operational, and management autonomy. Ribando Seelke et al. (2015) emphasize that with these measures PEMEX has more autonomy and a lower tax burden than before, and it is subject to competition from private investors. Under the four types of contractual models, PEMEX could work alone or in partnership with private companies.

6. In the case of exploration, PEMEX could continue exploration activities in the areas where it has recently made discoveries or investments based on its actual investment capacity and under a clearly established plan. In the case of not having positive results in three years, PEMEX must return these areas to the State. The possibility exists that this term could extends two more years.

7. In the case of hydrocarbon exploitation, PEMEX will maintain its rights in each of the fields that are in production at the time of issuance of the law.

Although it is too early to draw conclusions about the "Energy Reform," it is very clear that it implies not only radical changes for PEMEX itself, but also for Mexico. This change faces not only technical and financial challenges, but also cultural, considering that the nationalism of the Mexican oil and gas industry has profound historical traces that were reinforced by PEMEX´s success during its first forty years.

PEMEX Financial Paradox

In 2013, PEMEX was ranked eleventh among world´s top oil companies based on operational data (Table 1) (Energy Intelligence, 2013). According to Fortune Global 500, PEMEX is ranked forty-seventh worldwide in terms of total revenues (Fortune, 2015). According to the present PEMEX CEO Emilio Lozoya Austin (2015), in 2013, PEMEX´s production and finding and development costs were among the lowest in the industry ($8.09 and $17.97 per barrel of oil equivalent (BOE), respectively) (Table 2). Despite these positive performance indicators, PEMEX is a company with net losses because the taxes and duties regime imposed by the government have made it difficult for PEMEX to accumulate enough capital for its expansion. These taxes and duties are vital to the government, considering that in the period 1990-2009, Mexico had one of the region's lowest average income tax burdens on its citizens and businesses (less than 13% of the GDP), despite having a high average per capita income in relation to the regional average of Latin America (Gómez Sabaini and Jímenez 2012). Gómez Sabaini and Jímenez (2012) point out that, in 2004, 41.6% of the income taxes were not collected, with tax evasion being larger for corporations (46.2%) than individuals (38%).

Rank 2013	Rank 2012	PIW Index	Company	Country	State Ownership (%)*
1	1	27	Saudi Aramco	Saudi Arabia	100%
2	2	33	NIOC	Iran	100
3	3	39	ExxonMobil	US	
4	4	44	CNPC	China	100
5	5	49	PDV	Venezuela	100
6	6	62	BP	UK	
7	7	65	Royal Dutch Shell	The Netherlands	
8	10	86	Gazprom	Russia	50.002
9	8	92	Chevron	US	
10	8	94	Total	France	
11	12	98	KPC	Kuwait	100
11	11	98	Pemex	Mexico	100
13	15	99	Petrobras	Brazil	28.7
14	14	108	Sonatrach	Algeria	100
15	16	110	Lukoil	Russia	
16	19	114	Rosneft	Russia	75.16
17	17	118	QP	Qatar	100
18	18	123	Adnoc	UAE	100
19	21	150	Sinopec	China	75.79
20	20	160	Petronas	Malaysia	100v

Table 1: Top 20 of Energy Intelligence Rankings of the World's Oil Companies (Energy Intelligence, 2013).

Production Costs in 2013 per barrel of oil equivalent (boe)	
Petrobras	17.22
Chevron	17.10
Shell	14.35
BP	13.16
Conoco	12.35
Eni	12.19
ExxonMobil	11.48
Total	9.24
Statoil	8.51
PEMEX	**7.91**

Finding and Development Costs in 2013 per barrel of oil equivalent	
Total	32.40
Shell	25.77
Statoil	25.34
Petrobras	23.66
Chevron	21.35
ENI	19.99
Connoco	17.93
ExxonMobil	17.62
BP	15.19
PEMEX	**14.35**

Table 2. PEMEX´s production and finding and development costs (Lozoya Austin, 2015).

The Cantarell Collapse

Since 1979, Mexico´s oil production has relied upon the Cantarell Complex, discovered in 1976 offshore Campeche (southeast Mexico) (Figure 8). According to its ultimately recoverable reserves (11-20 Bbbl), the Cantarell Complex was ranked twelfth largest in the world, only behind the Middle Eastern and Venezuelan fields (Robelius, 2007). The oil produced from this complex is Maya type, 19-22° API, and the main pay zones are highly fractured-vuggy carbonate formations of Jurassic, Cretaceous, and Lower Paleocene age. From 1981 through 1993 Cantarell produced an average production of 1,000 Mbpd, equivalent to 40% of national production (Sánchez Bujanos et al., 2005; PEMEX, 2015b). In 1994, production began to decline as original reservoir pressure of 3,800 psia decreased to 1,520 psia, resulting in 25% reduction in well productivity (Kuo et al., 2001; Leon-G. et al., 2005).

In order to maintain the reservoir pressure, PEMEX began a program consisting of infill drilling, modernization, and expansion of production facilities in 1997 and the implementation of a nitrogen injection project in 2000 (Kuo et al., 2001; Sánchez Bujanos et al., 2005). These actions helped to increase production from 1,266 Mbpd in 1999 to a peak of 2,136 Mbpd in 2004. As a result, PEMEX reached a historical production record of 3,383 Mbpd. However, in 2005 Cantarell began a relatively rapid decline in oil production due to water encroachment and gas coning in the wells, in such a way that in 2008 oil production was 1,040 Mbpd; by 2012, was 454 Mbpd, and by 2014 only 375 Mbpd (PEMEX, 2015b) (Figure 9).

As a consequence of Cantarell´s collapse, Mexico has reduced exports 38% between 2004 (1,870 Mbpd) and 2014 (1,142 Mbpd); 80% of this crude was Maya crude oil (heavy oil) (PEMEX 2015a). This collapse has been partially compensated by the Ku-Maloob-Zaap Complex located next to Cantarell, in which the implementation of a pressure maintenance project by nitrogen injection in the year 2004 has caused an increase in oil production from 304 Mbpd in 2004 to 857 Mbpd in 2014 (PEMEX, 2015b). It is worthwhile noting that Mexico´s oil production is not only concentrated in very few fields, but it is also restricted geographically (southeast Mexico). PEMEX's inability to maintain budget independence from the federal government contributed to its failure to invest in new resource development projects.

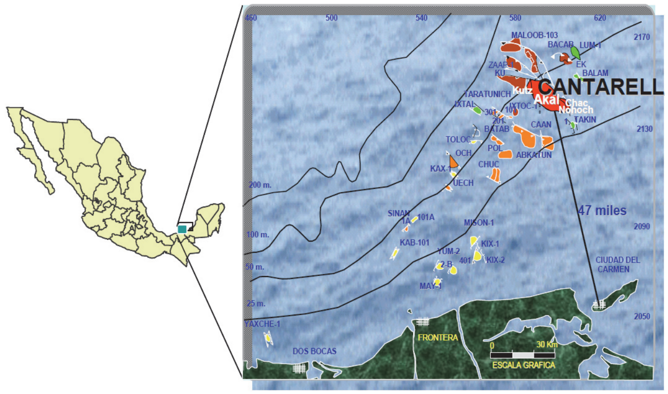

Figure 8: Cantarell complex location (Leon-G. et al., 2005).

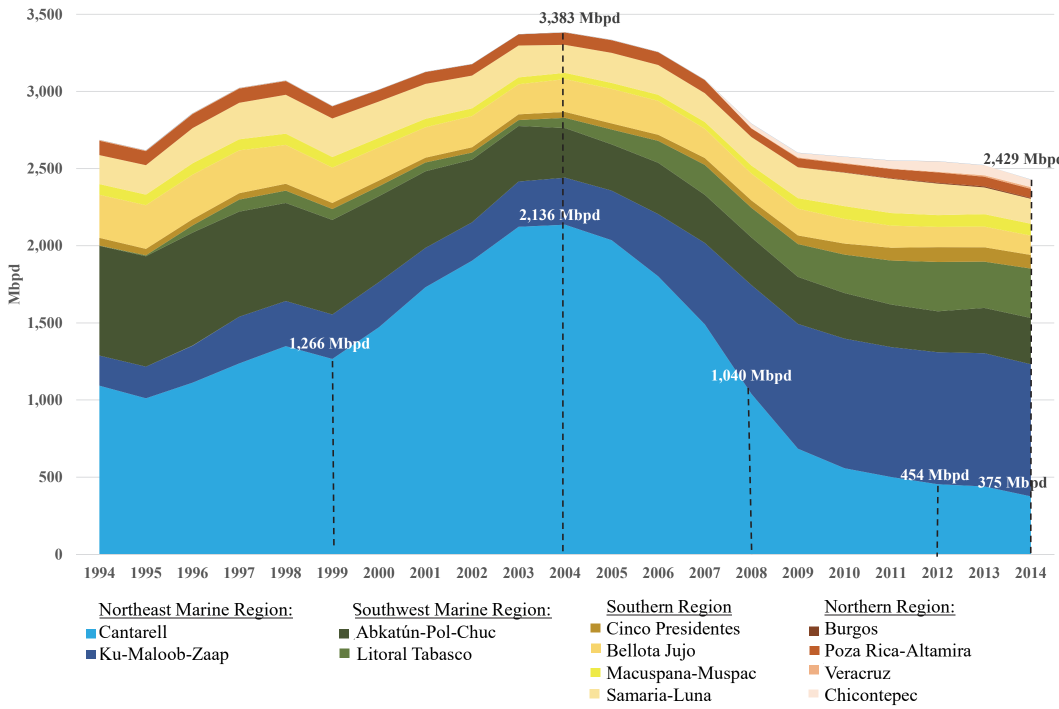

Figure 9: Mexico´s oil production by region and production assets[2] (graph made with data from PEMEX, 2015b).

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[2]In terms of production activities, since 2011, PEMEX is organized geographically into four regions and each of one is made up of production assets. The Northern Region has four production assets (Burgos, Poza Rica-Altamira, Veracruz, and Chicontepec), the Southern Region has four production assets (Cinco Presidentes, Bellota Jujo, Macuspana-Muspac, and Samaria-Luna), the Southwest Marine Region has two production assets (Abkatún-Pol-Chuc and Litoral Tabasco), and the Northeast Marine Region two production assets (Cantarell and Ku-Maloob-Zaap).

THE NATURAL GAS SHORTAGE

During the 1990s, governmental authorities decided that natural gas ceased to be a marginal fuel and became an essential feedstock for the Mexican economy. Thus, according to SENER (2008), natural gas entered into every production and consumption sector in a direct or indirect way, becoming a favorite fuel, able to harmonize economic and industrial progress with environmental preservation. In order to support this aim, PEMEX began to implement projects to reactivate the "mature" non-associated gas of northern and eastern Mexico (Burgos and Veracruz Basins).

As a result, at the end of the 1990s national production, mainly in the Burgos and Veracruz Basins, increased from 4,511 million cubic feet per day (MMcfd) in 2001 to 7,031 MMcfd in 2009. However, since that year production declined; 6,594 MMcfd by 2011, and 6,370 MMcfd by 2013 (Figure 10). In 2014, the increase in the production from wells with high gas-to-oil ratio in Ku-Maloob-Zaap and Cantarell helped to increase the national production by 3% (PEMEX, 2014a).

PEMEX´s natural gas production efforts have been surpassed by an ascending trend in consumption which climbed to 6,952 MMcfd in 2013 (SENER, 2014a). The most recent data from SENER (2014a) indicate that by 2013, the marketed natural gas was 4,492 MMcfd; therefore, Mexico imports increased to 2,517 MMcfd.

According to SENER (2014a), in 2013, Mexico´s natural gas demand was driven by the electric sector and the oil industry (80%). The remaining 20% was consumed by the industrial, residential, service, and transportation sectors. The expected demand forecast projected by SENER (2014a) considers that the electric and industrial sectors, and the oil industry will drive natural gas demand in the next thirteen years (99%).

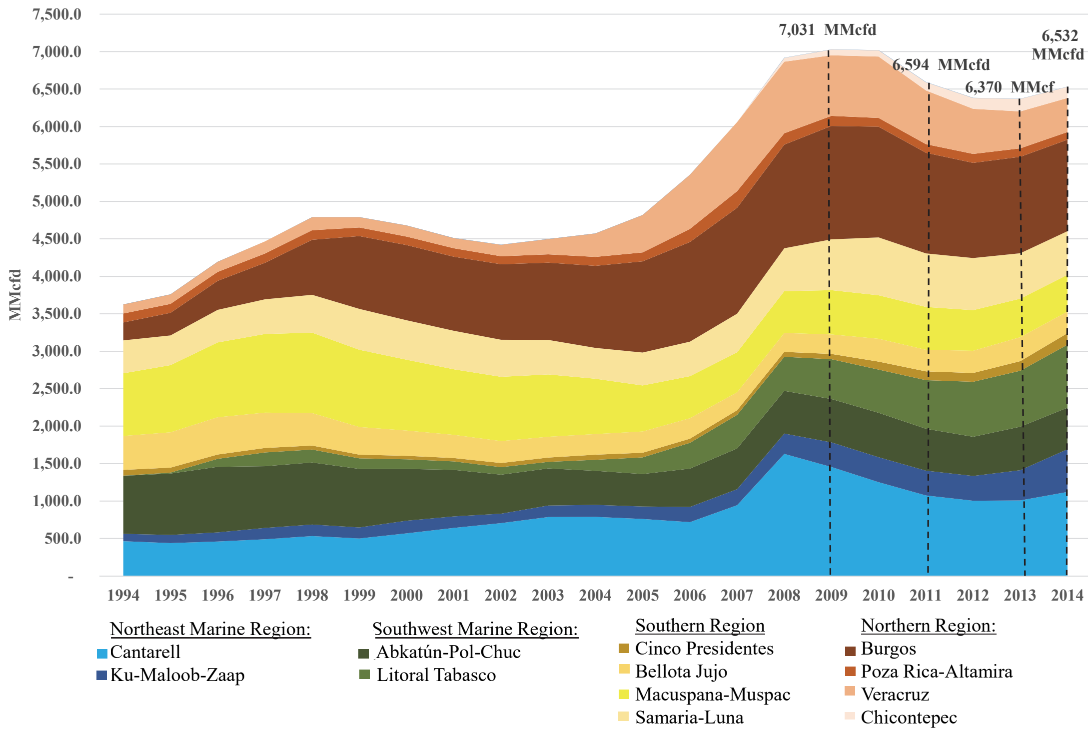


Figure 10: Mexico´s natural gas gross production by region and production assets (graph made with data from PEMEX, 2015b).

RESERVES AND RESERVES-TO-PRODUCTION RATIO

According to SENER (2015a), as of January 2015, Mexico´s proved oil and gas reserves were 13,017 MMBOE; probable reserves 9,966 MMBOE; and possible reserves 14,421 MMBOE; thus 3P is equal to 37,404 MMBOE. 75% of the 3P corresponds to crude oil, 8% to condensates and plant liquids, and 17% to dry natural gas (PEMEX, 2015a). 56% of 3P crude oil reserves are composed of heavy oil, 33% to light crude oil, and 11% to extra-light crude oil (PEMEX, 2015a). The reserves-to-production ratio is 10 years for 1P reserves, and 29 years for 3P. Proved reserves have declined 26% in the last eleven years, from 17.6 billion BOE in 2005 to 13.0 billion BOE in 2015 (PEMEX, 2015a) (Figure 11). According to PEMEX (2014), the prospective conventional and unconventional resources are 52.6 and 60.2 billion BOE, respectively (Figure 12). Most conventional and unconventional hydrocarbon reserves are located in east and southeast Mexico basins (Figure 12).

Proved natural gas reserves amounted to 15,291 Bcf, of which 65% consisted of associated gas and the remaining 35% non-associated gas (3P natural gas reserves totaled 54,890 Bcf, of which 68% consisted of associated gas and the remaining 32% of non-associated gas) (PEMEX, 2015a).

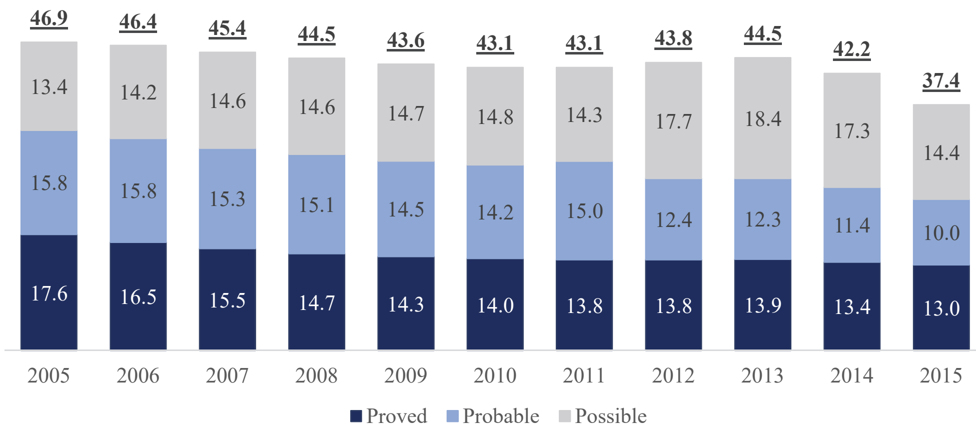
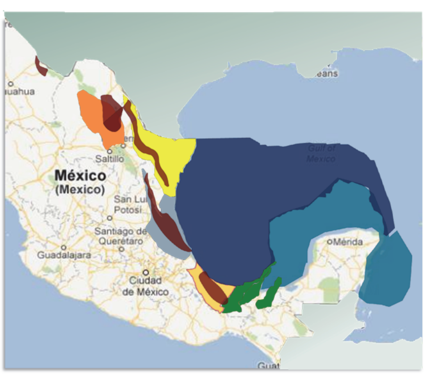


Figure 11: Evolution of Mexico´s reserves (billion BOE) (graph made with data from SENER, 2015a).



Basin	Reserves			Prospective resources	
	1P (90%)	2P (50%)	3P (10%)	Conv.	Non-conv.
Southeast	11.4	15.6	21.6	16.8	0.0
Tampico-Misantla	1.0	6.1	12.8	2.4	34.8
Burgos	0.3	0.5	0.8	3.0	10.8
Veracruz	0.2	0.2	0.2	1.4	0.6
Sabinas	0.0	0.0	0.1	0.4	14.0
Deep Water	0.1	0.5	1.9	27.1	0.0
Yucatán Platform	0.0	0.0	0.0	1.5	0.0
Total	**13.0**	**22.9**	**37.4**	**52.6**	**60.2**

Non-conventional (shale oil and gas)

Figure 12: Geographic distribution of Mexico´s hydrocarbon reserves and prospective resources (billion BOE) (modified from Lozoya Austin, 2015, with data from PEMEX, 2014a, 2015a; SENER, 2015a).

CONVENTIONAL RESOURCES

As of January 2014 Mexico´s prospective conventional resources were 52.6 billion BOE (PEMEX, 2014a; SENER, 2015a). The southeastern basins and deepwater of the Gulf of Mexico contain the largest shares of conventional resources, 32% and 51% respectively (Figure 12). These two areas have contrasting geological characteristics and economic and technological challenges. On the one hand, in the southeastern basins the application of new geological concepts and technologies have led to exploration opportunities in the traditionally high producing plays, both in the Mesozoic and Tertiary. New discoveries would be next to or near infrastructure. On the other hand, the deepwater areas of the Gulf of Mexico are challenging in terms of geology, economics, technology, and access to infrastructure.

Concerning areas located next to or near infrastructure, in 2013, Escalera Alcocer, Exploration Deputy of PEMEX, announced that the company had made four "significant shallow water discoveries" offshore Campeche: Ayatsil, Kayab, Xux, and Tsimin (Escalera Alcocer, 2013a) (Figure 13). Recent data from the SENER (2015b) indicate that in Ayatsil and Kayab, oil API gravity ranges from 10.5° to 8.6° and 3P reserves sum up 1,482.2 MMBOE. In Tsimin and Xux, the oil API gravity is 42.4° and 39.5°, respectively, and both fields sum up 912 MMBOE of 3P reserves (Table 3).

In 2008, Morales Gil former Director of PEMEX Exploration and Production communicated that in deepwater of the southern part of the Gulf of Mexico the company had discovered "important non-associated gas total reserves that represent in the short term an option to increase the national gas supply." He stated that the Lakach-1 well, located at a water depth of 988 m, produced 25-30 MMcfd from Lower Miocene sands. In 2013, Escalera Alcocer disclosed that PEMEX has discovered six fields near the Lakach field: Kunah, Piklis, Lalail, Nen, Noxal, and Leek (Escalera Alcocer, 2013a) (Figure 13). In addition, he stated that first production from Lakach is expected in 2015. Furthermore, he announced that in the Mexican part of the Perdido foldbelt, PEMEX had completed four wells: Trion-1, Supremus-1, Maximino-1, and PEP-1. According to SENER (2015b) the fields discovered in the southern part of the Gulf of Mexico sum up to 858.4 MMBOE 3P reserves; while those discovered in the Mexican Perdido foldbelt sum up 493.3 MMBOE 3P reserves (Table 3).

In the “2015-2019 Hydrocarbon Exploration and Extraction Bidding Plan” SENER (2015b) communicated that the Kayab field will be considered for the Round One bidding process; while the Lalail, Nen, Noxal, and Leek fields will be bid in Round Two. The Perdido area is considered for Rounds One, Two, Three, and Four, but no details are mentioned in this plan.

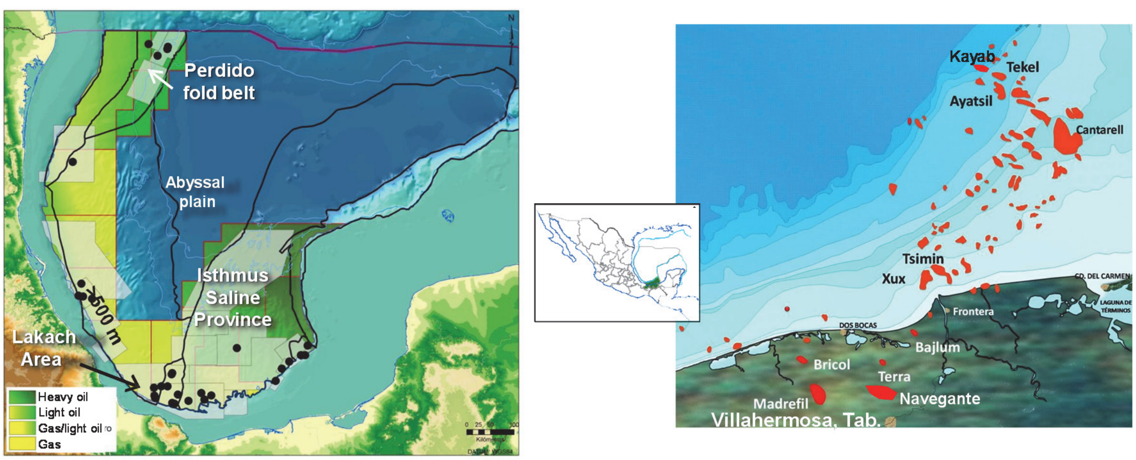


Figure 13: Location maps of main PEMEX´s discoveries in deep-water (modified from Escalera Alcocer, 2013a).

Location	Field	Area (km^2)	Type of Fluid	°API	1P (MMBOE)	2P (MMBOE)	3P (MMBOE)
Shallow Waters - Offshore Campeche	Ayatsil	59.5	Oil	10.5	316.2	567.7	592.8
	Kayab	54.3	Oil	8.6	184.3	231.7	889.4
	Xux	27.9	Oil	39.5	186.4	216	387.8
	Tsimin	50.6	Oil	42.4	395.2	450.2	524.2
						Total 3P reserves	**2,394.2**
Deepwater - Southern part of the Gulf of Mexico (offshore Veracruz)	Kunah	21.2	Natural Gas	0	0	184.9	299.1
	Lakach	20.6	Natural Gas	0	93.8	167.5	167.5
	Piklis	33.7	Natural Gas	0	0	111.4	111.4
	Lalail	14.3	Natural Gas	0	0	0	120.4
	Nen	3.1	Natural Gas	0	0	0	83.3
	Noxal	41.2	Natural Gas	0	0	0	76.7
	Leek	8.9	N/A				
						Total 3P reserves	**858.4**
Deepwater - Perdido Foldbelt (offshore Tamaulipas)	Trion	22.4	Oil	26.9	0	0	280.4
	Supremus	25.6	Oil	26.7	0	0	0
	Maximino	72.2	Oil	43	0	0	212.9
						Total 3P reserves	**493.3**

Table 3: Reserves and data of recent discoveries made by PEMEX in shallow and deepwater (data from SENER, 2015b).

Unconventional Resources

In 2013, the EIA estimated 545 Tcf and 13.1 Bbbl of risked technically recoverable shale gas and shale oil resources, respectively (Table 4). According to Escalera Alcocer (2013b), in Mexico, shale resources are distributed in five basins: Chihuahua, Sabinas, Burgos, Tampico-Misantla, and Veracruz. However, high uncertainty exists about the assessment because of the lack of detailed data and low level of drilling, for example, as of August 2015, CNH (2015), reported that total resources, including shale oil and gas, are approximately 31.9 Bbbl and 141.5 Tcf, respectively (Table 4). On the other hand, the U.S. Geological Survey (2014) (Schenk et al. 2014) assessed the Sabinas, Burgos, and Tampico-Misantla Basins at an estimated mean of 0.78 Bbbl for oil, 23.5 Tcf for gas and 0.9 Bbbl for natural gas liquids for these three basins (Table 4).

PEMEX has already begun the exploration of the Eagle Ford in the “provinces Sabinas-Burro-Picachos and Burgos” (Escalera Alcocer, 2013b; CNH, 2015). Geologically, these “provinces” comprise the Sabinas Coal Basin, the Mexican part of the

Maverick Basin, and the Burgos Basin. In addition, the Upper Jurassic Pimienta Formation has been evaluated in the Burgos and Tampico-Misantla Basins. Escalera Alcocer (2013b) recognizes that huge investments are required to overcome the challenge of evaluating and developing these unconventional resources in a sustainable way.

	CNH	EIA	USGS	CNH	EIA	USGS	USGS
Province	Oil (Bbbl)	Technically Recoverable oil and condensate (Bbbl)	Unconventional oil resources mean (Bbbl)	Dry and wet gas (Tcf)	Technically Recoverable natural gas (Tcf)	Unconventional gas resources mean (Tcf)	Natural Gas Liquids (Bbbl)
Tampico-Misantla	30.7	6.5	0.64	20.7	25.0	2.1	0.1
Burgos	0.0	6.3	0.14	53.8	393.0	15.6	0.6
Sabinas	0.6	0.0	0.0	67.0	124.0	5.8	0.2
Veracruz	0.6	0.3	Not quantitatively assessed	0.0	3.0	Not quantitatively assessed	Not quantitatively assessed
Chihuahua	Under Evaluation	No information	No information	Under Evaluation	No information	No information	No information
TOTAL	31.9	13.1	0.78	141.5	545.0	23.5	0.9

Table 4: Assessment of shale gas and shale oil resources in Mexico (EIA, 2013; Escalera Alcocer 2013b; CNH, 2015; Schenk et al., 2014).

THE CHICONTEPEC PROJECT UNCERTAINTY

The Chicontepec project is located in east-central Mexico in parts of the states of Veracruz, Puebla, and Hidalgo (Figure 14). It covers an area of 3,800 km^2 and was identified in 1926 by the Anglo-Dutch partnership El Águila and later abandoned in favor of more easily accessible oil (Breglia, 2013).

Based on internal studies and the reserve certification of petroleum consulting firms, PEMEX has launched three main campaigns to exploit these reserves. In the early 1950s, at the end of the 1970s, and the most ambitious project that started in 2003 (CNH, 2010b). These campaigns have been the subject of much controversy because the high expectations that have been raised and the disappointing results. In November 1978, PEMEX´s former CEO Jorge Díaz Serrano disclosed that the Chicontepec field "is one of the largest in the Western Hemisphere, containing about 100 billion bbl of oil and 40 trillion cu ft of natural gas in place" (Oil & Gas Journal, 1978). According to Sordo and López (1988) this project began with a goal of producing 53 Mbpd by 1981; however, the production in that year only reached 15 Mbpd. For this reason and due to the high performance of the wells drilled in the Mesozoic rocks of Chiapas-Tabasco and offshore Campeche areas (southeast Mexico), the Chicontepec project was delayed.

The Late Paleocene-Middle Eocene Chicontepec Formation consists of shales or silty shales with the rest of the formation made up of multiple thin sandstone beds and zones of sandstone beds. Typically, between 8 and 16 major laminated sandstone reservoirs are present at a depth of around 2,500 m. Permeability range from 0.1 to 10 mD and porosity varies from 5% to 15%. Oil gravity ranges from 18° to 45° API (Gachuz-Muro and Sellami, 2009). Reservoirs are found at depths ranging from 1,000 to 2,500 m and have the bubble point pressure near the initial pressure (Morales Gil, 2009). Hence, the reservoir and geological characteristics of this formation have led to the historically low productivity of their wells. According to Cheatwood and Guzmán (2002) "initial flow rates are variable, but with an average initial production rate of approximately 120 barrels per day. The well production declines rapidly and then stabilized at around 40 barrels per day where it goes on a secondary decline."

According to Guzmán (2001), in Chicontepec, the OOIP was 139 Bbbl, the OGIP was 50 Tcf, and the total reserves were 13,762 MMb of crude oil and 26.2 Tcf of dry gas. Former PEMEX CEO Raul Muñoz Leos disclosed that in 2003 the company launched "Proyecto Integral Chicontepec" which would require an investment of $310 billion pesos over a period of 15 years to develop Chicontepec fully, and the project would require drilling 13,500 wells (Muñoz Leos, 2006). Thus, investment reached US$3,813 million between 2004 and 2009 allowing intensive drilling (CNH, 2010b). During these years, the

Chicontepec project began to be named officially Aceite Terciario del Golfo (ATG). After the period of heavy investments, in 2009 Morales Gil declared that the Chicontepec exploitation requires more than 17,000 wells or an average of 1,000 wells per year, and he stated that the goal is to produce 100 barrels per day per well (Cruz Serrano, 2009). In 2011, Morales Gil announced before a Special Commission of Congress (Cámara de Diputados LXII Legislatura, 2011) that: "Chicontepec produces 50 Mbpd and that by 2012 production will increase to 100 Mbpd." In 2012, in another appearance before a Special Commission of the Congress (Cámara de Diputados LXII Legislatura, 2012) Morales Gil stated that "Chicontepec has an excellent production of 70 Mbpd, and we think that by 2015 it will reach 150 Mbpd." In the same year, Narváez Ramírez (2012) stated that by 2030 Chicontepec production will peak at 501 Mbpd and that the EUR will be 5,373 million barrels in the period 2012-2072.

Morales Gil (2009) pointed out that the main technological challenges in the ATG Project are: "high geological complexity, the heterogeneity of the rock, multiple accumulations with limited vertical communication, early liberation of gas, and low permeability." Recent data disclosed by PEMEX (2015a) indicate that the OOIP is 81 Bbbl, the OGIP is 43 Tcf, and the total reserves are 7,494 MMb of crude oil and 21.9 Tcf of dry gas. These OOIP and OGIP estimates are substantially lower than those made in 1978 and 2001; while from 2001 to 2015 the total oil and gas reserves have decreased 46% and 16%, respectively.

Data from PEMEX (2015b) indicate that Chicontepec produced 29.3 Mbpd in 2008, 40.9 Mbpd in 2010, 68.5 Mbpd in 2012, 48.7 Mbpd in 2014, and by the end of the first quarter of 2015, 42.7 Mbpd. As of January of 2015, PEMEX reported that the 3P reserves of the country decreased 12% from the previous year because of "the non-favorable water injection pilot test used as a secondary recovery method in the ATG fields" (PEMEX, 2015a). Furthermore, PEMEX declared that it will continue developing technological tests with the aim of increasing the recovery factor because the potential of the ATG is still one of the most important of the country."

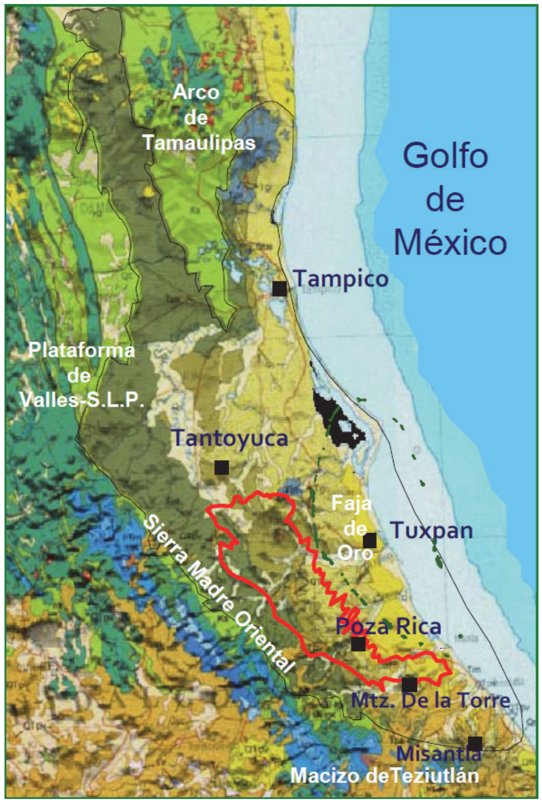


Figure 14: Location map of the Chicontepec project (CNH, 2010a).

Chapter 3: Geological Framework of the Eagle Ford Group and Equivalent Formations in Mexico

The purpose of this chapter is to examine a regional geological screening in order to provide a sound analogy between the Eagle Ford play of Texas and the areas of northeast and east Mexico where the Eagle Ford Group is a prospective shale unit (EIA, 2013; Schenk et al., 2014; CNH, 2015). A line of reasoning for these assessments relies upon the statement that Mexico's organic-rich shales "correlate with productive Jurassic and Cretaceous shale deposits in the southern U.S., notably Eagle Ford" (EIA, 2013). However, few data are publically available on the geological backgrounds that demonstrate a straightforward correlation. Hence, an analysis of these data and information is critical to identify the main constraints of the analogy, and the challenges that must be overcome to unlock the potential of the Mexicans areas where the Eagle Ford Group is present. With this review, the geologic knowledge and experience gained in Texas to the Mexicans basins will be more applicable.

In order to achieve the goal, I describe the regional structural framework of Texas and northeast and east Mexico where the Late Cenomanian-Turonian strata were deposited. Then, I compare the regional stratigraphic characteristics of the Eagle Ford Group and their equivalent formations in northeast and east Mexico. Finally, I provide the tectonic and paleogeographic development of the Eagle Ford Group.

In comparison with Mexico, there is a strong understanding of the Eagle Ford shale in Texas including the main geological controls on its lithostratigraphy, biostratigraphy, organic geochemistry, thickness and depth variations, paleogeography, sequence stratigraphy, regional structure, and petrophysics (e.g., Hentz and Ruppel, 2010, 2011; Hentz et al., 2014; Donovan et al., 2012). These studies and the available information on

Mexico may shed light and help identify the similarities and differences between the Texas Eagle Ford Group and equivalent formations in Mexico.

STRUCTURAL FRAMEWORK

According to Ewing (1991, 2012), the Mesozoic-Cenozoic tectonic events in the northern and western part of the Gulf of Mexico Basin produced sedimentary basins and intervening platforms or arches that are second-order structures or sub-provinces of three major structural provinces: the Interior Zone, the Coastal Zone, and the Western Compressional Zone (Figure 15).

In Texas, the Eagle Ford Group is present in the Interior Zone Province which is made up of Mesozoic structures and covers two physiographic provinces: the northern coastal plain of the Gulf of Mexico and the southern part of the Great Plains. This structural province consists of a west-east trend of basins and uplifts that are limited to the south by the Early Cretaceous shelf margins, and to the north by the Balcones-Mexia-Talco fault systems. These second-order structures are, from east to west, the Sabine uplift, the East Texas Basin, the Llano-San Marcos uplift, and the Maverick Basin. The Eagle Ford play extends in the Maverick Basin and the adjacent western San Marcos arch (Hentz and Ruppel, 2010; Hentz et al., 2014). During the Albian and Neogene, the Interior Zone was subjected to tensional stresses that produced the Karnes Trough, and the Balcones-Mexia-Talco fault zone of central Texas, respectively (Eargle, 1959; Tucker, 1968; Ewing, 1991). According to Ewing (1991) the Laramide compression developed a zone of northwest-trending low-amplitude folds in the Maverick Basin. As a consequence, with the exception of the Maverick Basin, the regional structure of the Interior Zone is relatively simple with a gentle coastward dip and a peripheral belt of normal faults. Locally, the structure is more complex owing to salt tectonics and because the subdued uplifts are oriented nearly normal to the strike of the Balcones fault zone (Cartwright, 1932; Laubach and Jackson, 1990; Sharp and Banner, 1997).

The Coastal Zone covers Texas and northeast Mexico and extends from Louisiana to Tamaulipas throughout the northern and northwestern part of the Gulf Coastal Plain. The Mesozoic history of subsidence of this province is concealed by a 10-15 km thick Upper Cretaceous-Cenozoic coarse clastic sequence that progrades into the Gulf of Mexico forming growth-fault systems and salt diapirs (Ewing, 1991).

In northeast and east Mexico, most of the formations equivalent to the Eagle Ford Group of Texas were deposited in basins and arches/uplifts corresponding to the Western Compressional Zone. These basins and arches/uplifts are fundamental landforms of the Late Triassic-Early Jurassic paleogeography which were drastically deformed by the Laramide orogeny and to a minor degree by a Neogene deformation (Wilson, 1990; Salvador, 1991a). Therefore, the Western Compressional Zone is considerably more complex than the Interior Zone. In Mexico, the Compressional Zone encompasses three physiographic provinces: the Western Gulf coastal plain, the foothills of the Sierra Madre Oriental, and the northeastern Mexico Highlands. In the study area, this province comprises the Tampico-Misantla and Sabinas Basins, the El Burro-Picachos uplift, the Tamaulipas arch, and the Coahuila platform. In general terms, the Frontal Ranges that form the El Burro-Picachos uplift and the Tamaulipas arch constitute the boundary between the Interior Zone and Coastal Zones Provinces with the Western Compressional Zone.

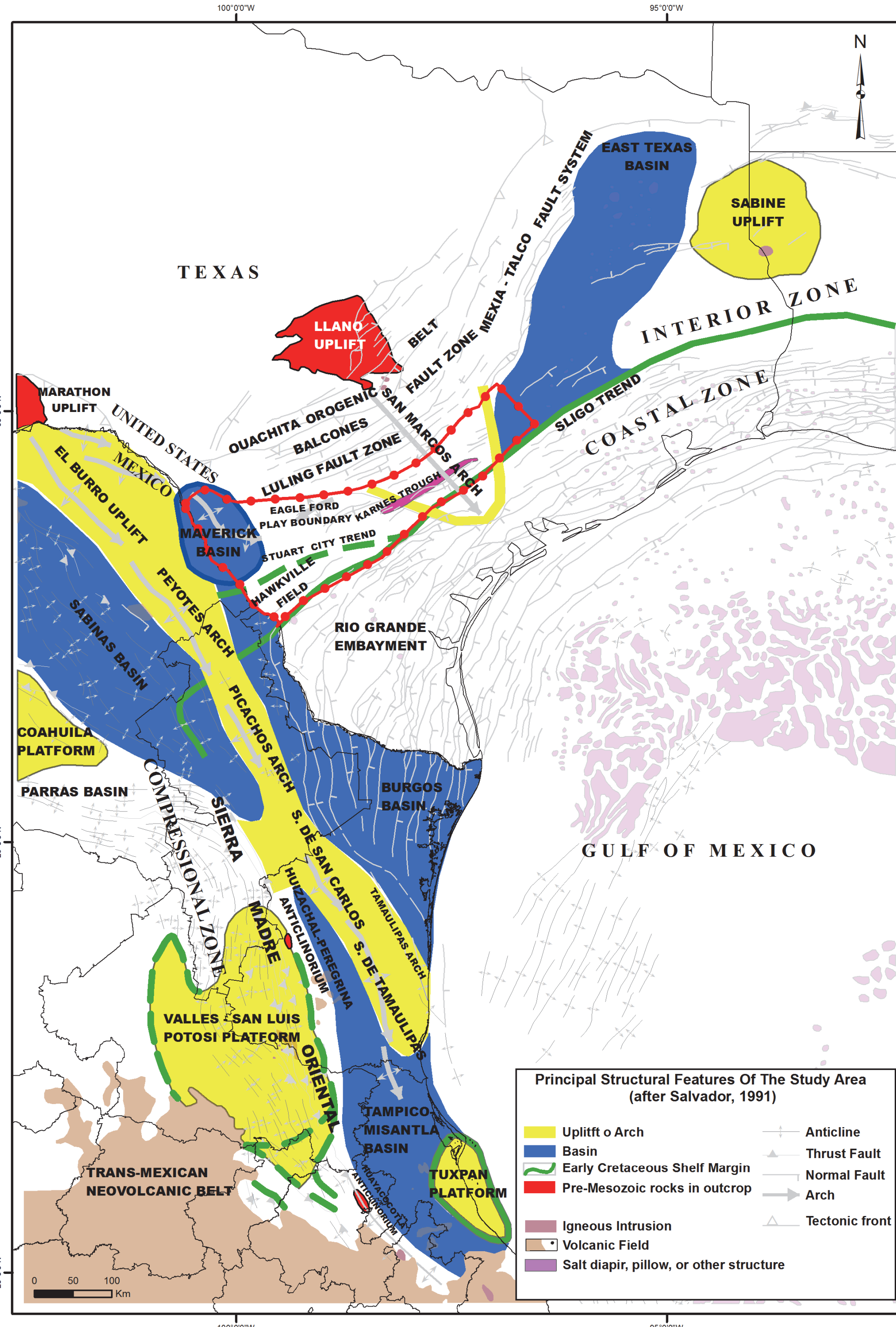


Figure 15: Principal structural features of the study area (after Salvador, 1991b).

The Interior Zone Province

The Llano-San Marcos Uplift

The Llano-San Marcos uplift is a basement high that make up a broad structural nose plunging gulfward. This uplift separates the Rio Grande Embayment from the East Texas Basin (Halbouty, 1966). At the surface, it is reflected by a gentle southeast convex arch of Upper Cretaceous and Early Tertiary strata (Figures 15 and 16). In the subsurface, isopachous studies reveal thinning of various sequences across the arch including the Eagle Ford (Murray, 1961). Three major normal fault belts cross the San Marcos arch in a southwest-northeast direction: Balcones, Luling, and Charlotte-Jourdanton (Fowler, 1956). The occurrence of igneous rocks between the Balcones and Luling fault belts led Ewing and Caran (1983) to speculate about a relationship between the magma and the extensional stresses produced by these faults.

Maverick Basin

The Maverick Basin is an ovate tectonic basin encircled by "reefs" that was formed during the Aptian, when an event of differential subsidence took place between the Llano -San Marcos uplift and the El Burro-Picachos uplifts (Figures 15 and 16) (Winter, 1961; Loucks, 1977; Smith, 1981; Rose, 1986). This basin is mostly filled with Cretaceous mudstones and limestones and a veneer of Upper Cretaceous and Lower Tertiary clastics (Scott, 2004). Recent seismic reflection data reveal a graben or half-graben filled with metamorphosed Paleozoic sediments that unconformably overlie red beds of Early Mesozoic age (Ewing, 2010; Scott, 2004).

The Maverick Basin is located in the northwestern part of the Rio Grande Embayment. Ewing (1987) argued that the boundary between the Maverick Basin and the Llano-San Marcos uplift is a linear zone 16 km width and 160 km length that he called

"Frio River Line" (Figure 16). This author observed that this Line marks the transition of five critical geological elements: the termination of the Balcones and Luling faults; the dying out of Laramide orogeny folds; the termination of the Balcones igneous belt in a zone of intense volcanism; the ending of the Mexia-Talco graben system; and the divergence of Sligo and Stuart City reef trends where the Hawkville field is present (Figures 15 and 16). The effects of the Laramide orogeny in the Maverick Basin were gentle but significant. They produced the inversion of the Pre-Late Jurassic graben into broad anticlines (e.g., Chittim anticline) that plunge to the southeast (Rose, 1986; Ewing, 2012).

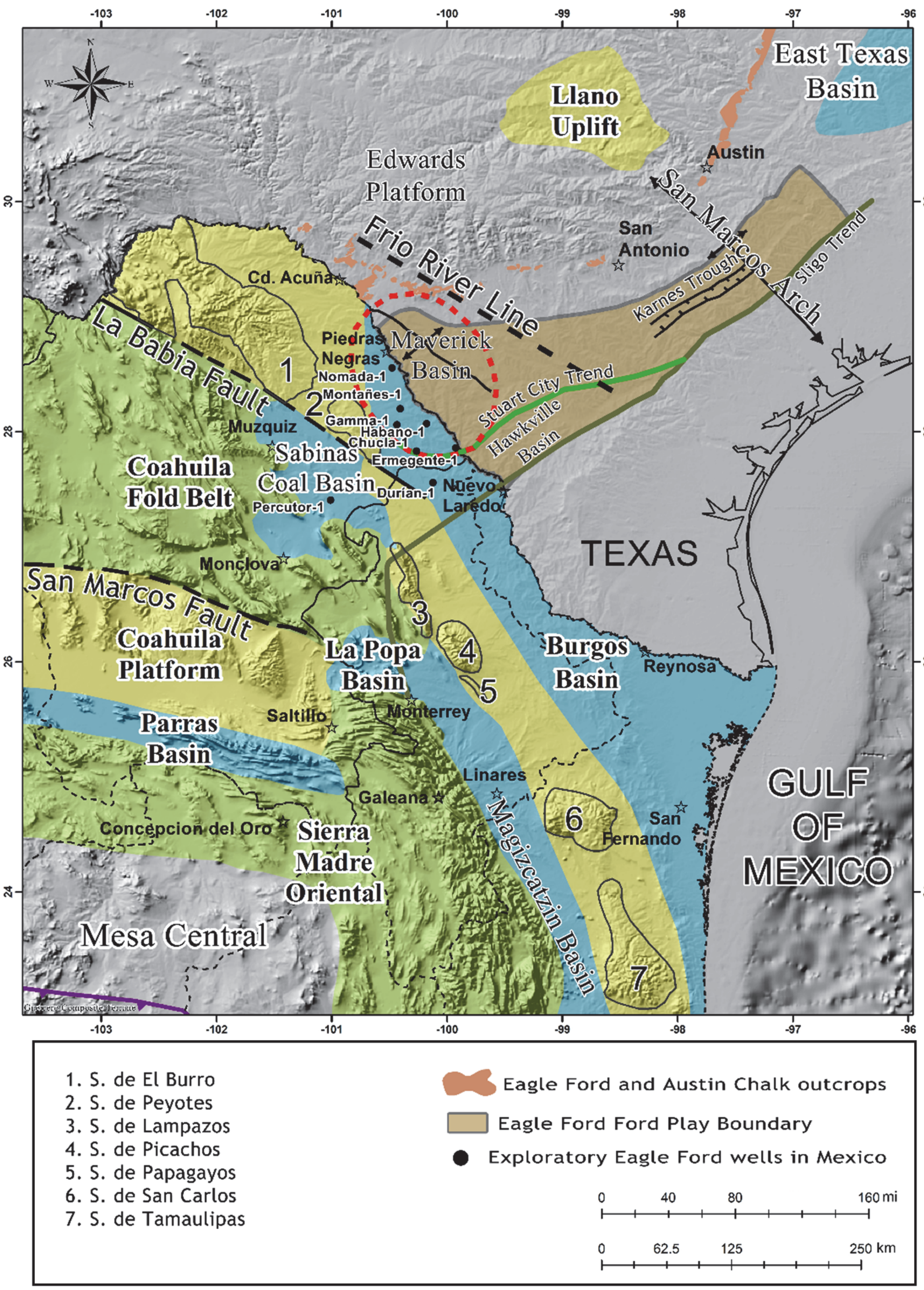


Figure 16: Regional map showing the Eagle Ford play boundary, the main structural features of Texas and northeast Mexico, and the exploratory Eagle Ford wells in Mexico (data from different sources mentioned in the text; EIA, 2014a; CNH, 2015).

The Coastal Zone

The Burgos Basin

The Burgos Basin lies at the southern part of the Rio Grande Embayment and constitutes a monocline dipping to the Gulf of Mexico. Its basement rocks are the crystalline rocks that made up the eastern flank of the El Burro-Picachos uplift and the Tamaulipas arch (Figures 15, 16, and 17). Subsidence of this depocenter began in the Middle Jurassic and during the Mesozoic a section of 3,000 m thick carbonates, evaporites, and siliciclastics was deposited (Echanove Echanove, 1986; Eguiluz de Antuñano, 2011a). During the Cenozoic, this depocenter was filled with more than 5,000 m of continental, paralic, and deltaic sediments, which display numerous transgressive and regressive cycles (Echanove Echanove, 1986; Eguiluz de Antuñano, 2011a). According to Kane (1936), Perez Cruz (1993), and Eguiluz de Antuñano (2011a), the Laramide orogeny produced faulting and low-amplitude anticlines in the Mesozoic-Early Tertiary section. At the end of the Eocene, this tectonic event was followed by a general progradation of the shelf margin that produce zones of normal growth faulting (Echanove Echanove, 1986; Eguiluz de Antuñano, 2011a). The Eagle Ford crops out along the flanks of the El Burro-Picachos uplift and dip towards the east.

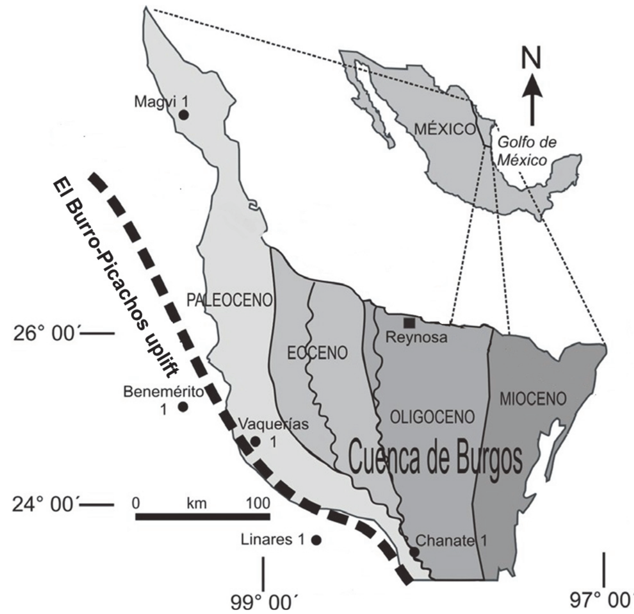


Figure 17: Regional sketch of the Burgos Basin (Eguiluz de Antuñano, 2011a).

The Western Compressional Zone

El Burro-Picachos uplift and the Tamaulipas arch (Front Ranges)

These sub-provinces constitute a trend of hills and mountains extending in a northwest-southeast direction from the U.S.-Mexico border into the environs of Tampico, which were described by Tatum (1931) with the name of "Front Ranges." Tatum included from northwest to southeast the Sierra de Burros, the Peyote Hills, the Sierra de Vallecillos, the Sierra Lampazos, Sierra Picachos, Sierra Papagayos, Sierra de San Carlos, and Sierra de Tamaulipas (Figure 16). According to Padilla y Sánchez (1982) these Front Ranges formed broad, often breached, and symmetric anticlines that contrast sharply with the folds of the Sierra Madre Oriental. The Front Ranges make up the hinge line between the Sabinas Basin and the Maverick and Burgos Basins (Figures 15 and 16).

El Burro-Picachos uplift was an emergent land since the Early Jurassic and was progressively covered from southeast to northwest by the Late Jurassic and Cretaceous seas

(Salvador, 1987, 1991c). In general, this uplift plunges and decreases in elevation to the southeast exposing Paleozoic metasedimentary rocks at the northwestern end (Sierra del Carmen) and Lower and Upper Cretaceous (Eagle Ford Group) to the southeast. In the middle and southeastern part of the trend, numerous exploratory wells have penetrated schists and phyllites of probable Permian age (Flawn and Maxwell, 1958; Flawn and Díaz, 1959; Padilla y Sánchez, 1982; Denison, 1970).

According to Charleston (1981), the limit between the El Burro-Picachos uplift and the Sabinas Basin is a left - lateral strike - slip fault that he named the La Babia fault. Padilla y Sánchez (1982) and Ewing (2012) described this fault with the names of Boquillas-Sabinas lineament or La Babia-Zapata zone, respectively (Figure 16).

Tatum (1931) named the north-northwest trending frontal range “Tamaulipas arch”, located in central and southern Tamaulipas (Figures 15, 16, and 18). This range corresponds to the Sierra de San Carlos and the Sierra Tamaulipas, which form a low, broad arch with Tertiary intrusions at their core (López Ramos, 1982) (Figure 18). Tatum (1931) and Imlay (1943) postulated that the Sierra de San Carlos and the Sierra de Tamaulipas constituted a Jurassic emerged land that was the southward continuation of the El Burro-Picachos uplift. Also, these authors state that these front ranges were the buttress for the Laramide orogeny compressive stresses. Wells such as Lantrisco-1, Chaneque-1, and Trincheras-1 demonstrated the existence of an emergent land in the Sierra de San Carlos (Padilla y Sánchez, 1982).

In the Sierra de Tamaulipas, Muir (1936) named Turonian thin-bedded limestones with bituminous black shales at the base “Agua Nueva Formation”, which are “scarcely different” from the Eagle Ford Group (Figure 18).

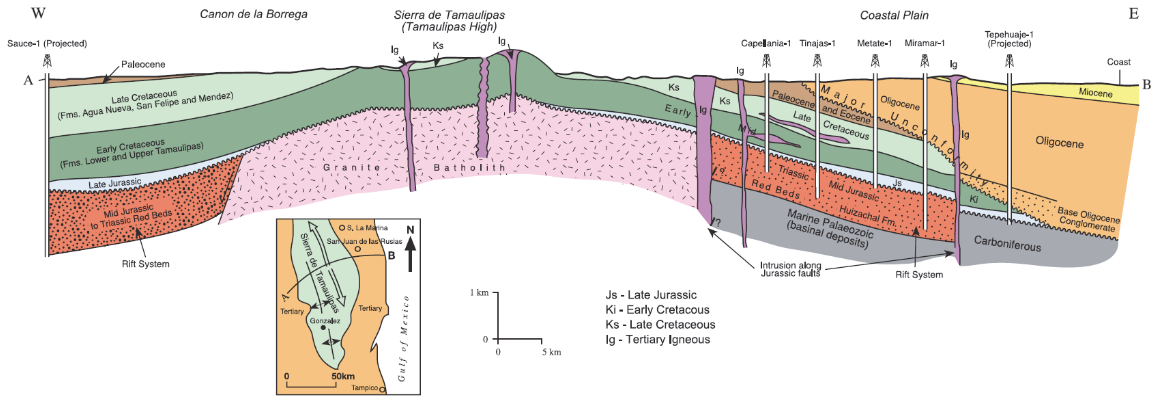


Figure 18: Schematic cross section through the Sierra de Tamaulipas (modified after López Ramos, 1982 by Horbury et al., 2003).

Sabinas Basin

The term Sabinas Basin was first used to describe a paleogeographic Late Jurassic embayment (Gulf of Sabinas) formed between the Coahuila platform, the El Burro-Picachos uplift, and the Tamaulipas arch (Humphrey, 1956; Salinas E., 1969). Continued subsidence, relative sea-level changes and the erosion of basement uplifts gave rise to a sedimentary section 4,000 m thick (Salinas E., 1969; Cuevas Leree, 1984; Eguiluz de Antuñano, 2001). Charleston (1981) and Padilla y Sánchez (1982) agree that the boundaries between the Gulf of Sabinas and the El Burro-Picachos uplift and the Coahuila platform are northwest regional lineaments. The northern lineament is called either La Babia (Charleston, 1981) or Boquillas-Sabinas (Padilla y Sánchez, 1982). The southern lineament is named either San Marcos (Charleston, 1981) or Sierra Mojada-China (Padilla y Sánchez, 1982) (Figure 16).

The Laramide orogeny severely deformed the Gulf of Sabinas producing three structural styles: the Coahuila Marginal Fold Belt (Murray, 1961); La Popa Basin (McBride et al., 1974), and the Sabinas Coal Basin (Humphrey, 1956; Robeck et al., 1956) (Figure 16). The Coahuila Marginal Fold Belt consists of long narrow northwest-oriented anticlines separated by broad synclines at the northwest. Lower and Middle Cretaceous carbonates crop out at the crests of the long anticlines (Figure 19). The Eagle Ford Group crops out at the flanks of the anticlines of this foldbelt.

La Popa Basin lies at the southern edge of the Coahuila Fold Belt and according to Giles et al. (1999), it contains Lower Albian-Eocene rocks deposited coevally with diapirism. These authors use the name of Indidura Formation (Kelly, 1936) to describe the rocks equivalent to the Eagle Ford Group.

The Sabinas Coal Basin lies between the Coahuila Marginal Fold Belt and the El Burro-Picachos uplift and consists of as a set of eight broad synclines with Campanian-Maastrichtian fluvial-deltaic deposits (Robeck et al., 1956). According to Flores Espinosa (1989), the Sabinas Coal Basin is filled with ~1,500 m of Campanian-Paleocene fluvial-deltaic sediments and its subsidence was associated with southwest-northeast directed crustal shortening of the Coahuila Marginal Fold Belt. These clastic rocks conformably overlie the Eagle Ford Group, and they are correlated with the fluvial-deltaic sediments that filled the Maverick, La Popa, and Parras Basins. In the three basins, sediments were transported axially into the basins by rivers flowing from west to east (Weise, 1979; Tyler and Ambrose, 1986; Flores Espinosa, 1989; Bermúdez Santana, 2003). Published seismic information reveals that the Sabinas Coal Basin was mildly folded, and the sedimentary section pinches out towards the El Burro-Picachos arch (Eguiluz de Antuñano, 2011b) (Figure 19).

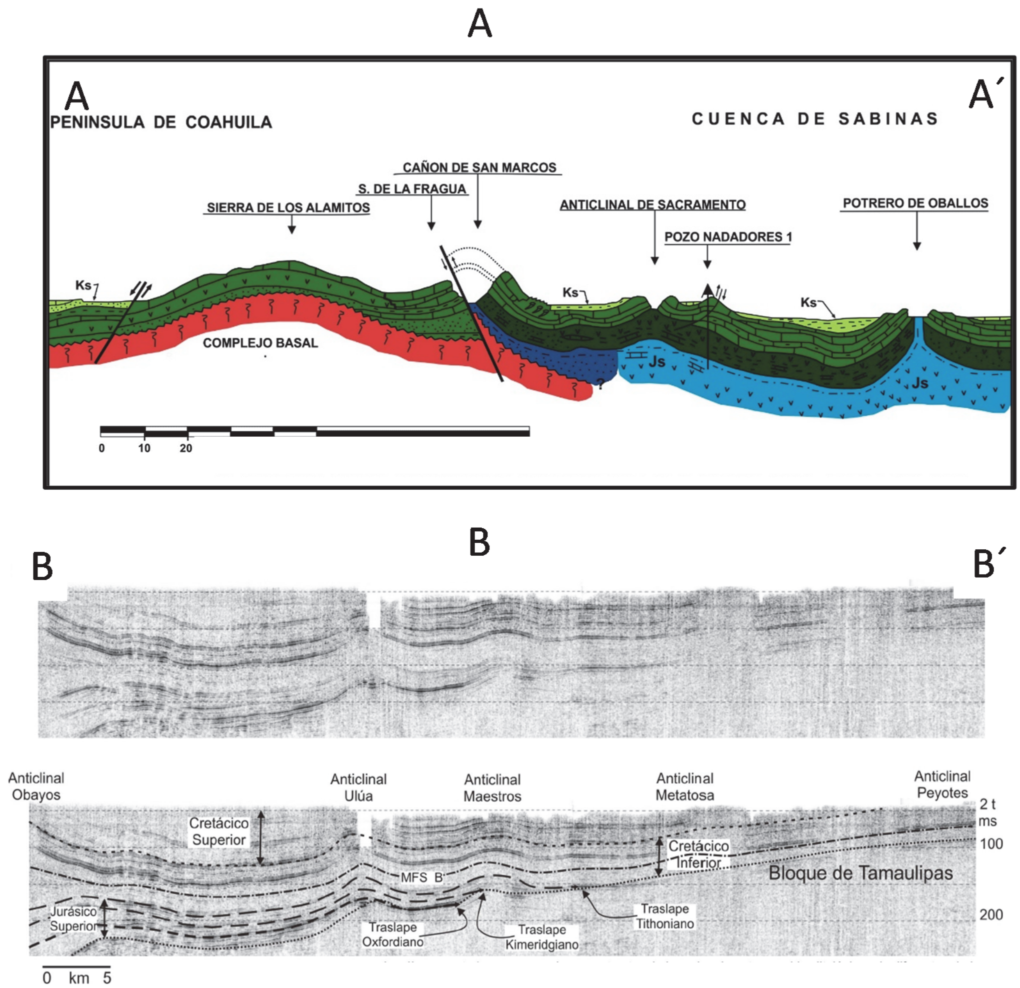


Figure 19: Structural styles across the Coahuila platform and the El Burro-Picachos uplift. A) A-A´ cross section across the Coahuila platform and the Coahuila Fold Belt (redrawn from Serrano and Garza in Garza 1977). B) B-B´ cross section across the Sabinas Coal Basin and the El Burro-Picachos uplift (Sierra de Peyotes) (Eguiluz de Antuñano, 2011b). See Figure 27 for the approximate location of these sections in a regional context.

The Coahuila Platform

The Coahuila platform is also known as the Coahuila Peninsula because its crystalline basement was a structural part of the North American continent (Böse, 1923; Kellum et al., 1936). Kellum et al. (1936) point out that the Coahuila platform was a Late Jurassic continental area which began to be covered by marine water during the Late

Aptian. These authors observed that this platform was formed by broad and relatively simple anticlines in comparison with the Sierra Madre Oriental folds (Figures 15 and 16). The trend of these folds is northwest and they expose Lower Cretaceous carbonates at their crests and Upper Cretaceous rocks at their flanks (Padilla y Sánchez, 1982). In the southeastern part of this platform, Kelly (1936) observed that the shales and thin-bedded limestones equivalents to the Eagle Ford Group contain more siliciclastics. Hence, he proposed the name of Indidura Formation to describe these rocks.

Tampico-Misantla Basin

The Tampico-Misantla Basin is a Mesozoic-Cenozoic depocenter with a crystalline basement that is the southward continuation of the Tamaulipas arch. Petrographic studies have demonstrated that in the subsurface of the Tampico-Misantla Basin, the Tamaulipas arch is made up of Late Paleozoic schists and Permo-Triassic granites (Quezada Flores, 1961; López Infanzón, 1986). This basin extends from the foothills of the Sierra Madre Oriental to the Gulf coastal plain and the continental platform of the Gulf of Mexico (Figures 15 and 20). The boundary between the Tampico-Misantla Basin and the Burgos Basin is the Sierra de Tamaulipas. Its most prominent Mesozoic feature is the Tuxpan platform where the Golden Lane Atoll developed on a major relict of the Tamaulipas arch. The Late Cenomanian-Turonian rocks equivalent to the Eagle Ford Group are found in the subsurface of this basin, and they crop out at the eastern front of the Sierra Madre Oriental. This unit has been named Agua Nueva Formation, which, along with the San Felipe Formation (Coniacian-Santonian), were the first commercial oil reservoirs discovery in Mexico in 1904 (Ebano-Panuco field). Since then, these rocks have been the main heavy-oil producer reservoirs of this field. Reservoir storage and flow is entirely from open fractures associated with basement tectonics (Galicia et al., 2006).

The Mesozoic-Early Cenozoic development of the Tampico-Misantla Basin is strongly related to the Late Triassic - Late Jurassic opening of the Gulf of Mexico and to the effects of the Laramide orogeny. The first event produced horst and graben topography that influences the thickness and distribution of facies of the Mesozoic section (Figure 21). During the Laramide orogeny, the tectonic stacking of Sierra Madre Oriental produced a foreland basin where the Chicontepec and the Bejuco-La Laja Canyons developed between the fold belt and the Tuxpan platform. At the end of the Eocene, the erosion of the Sierra Madre foldbelt front produced a gulfward gently sloping plain, in which terrigenous clastics rocks become successively younger to the east (López Ramos, 1982; Yurewicz et al., 1997) (Figure 21).

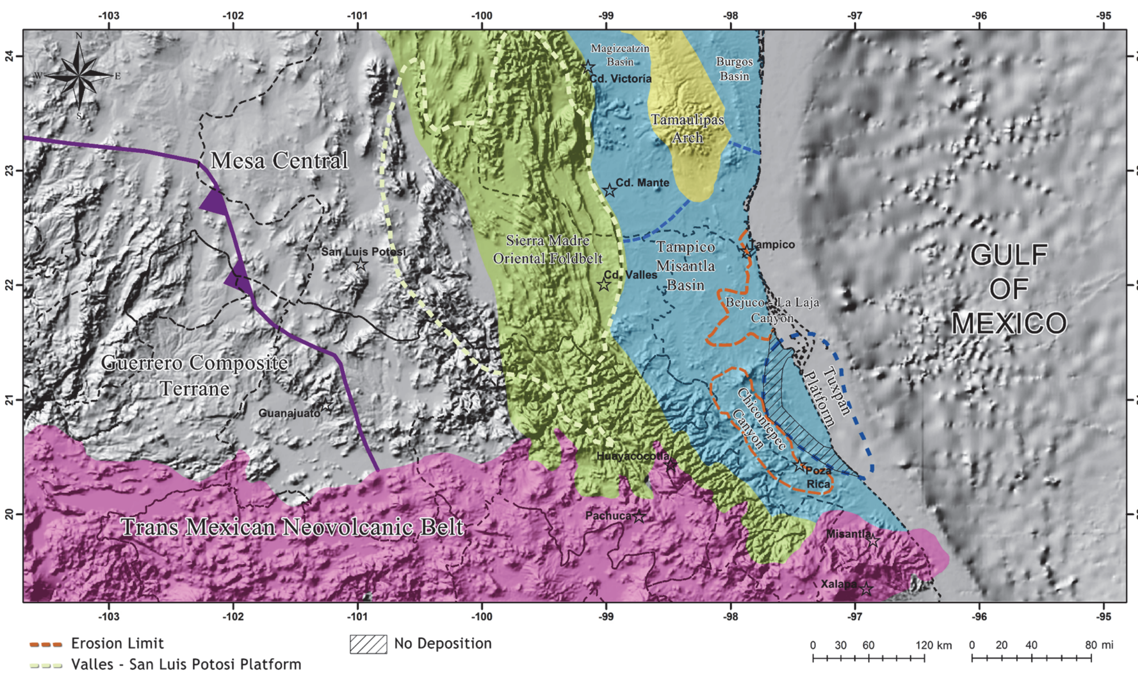


Figure 20: Regional map showing the tectonic setting of the Tampico-Misantla Basin (data from different sources mentioned in the text).

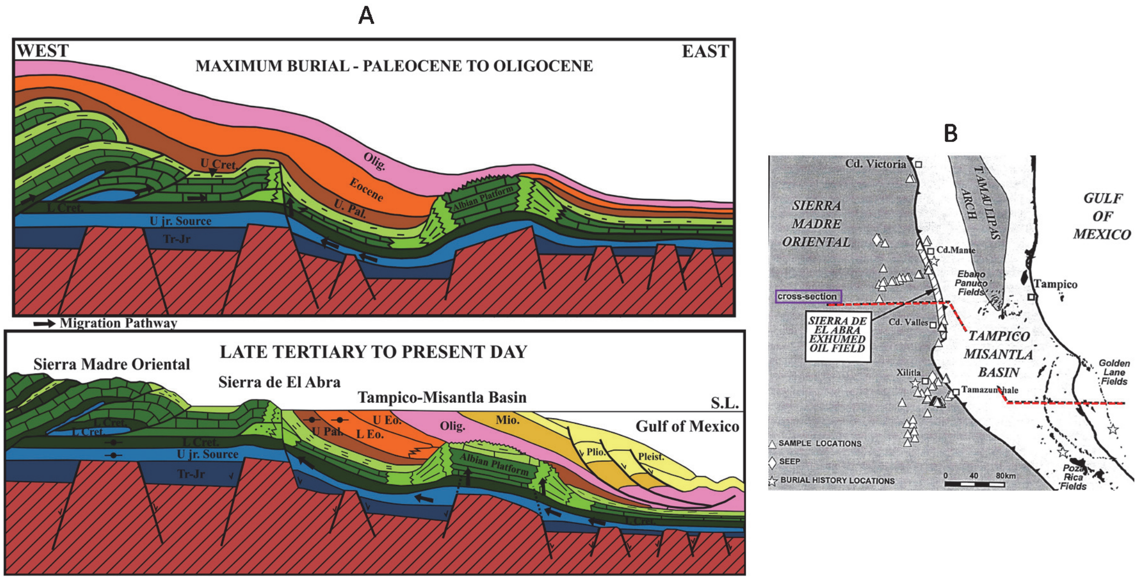


Figure 21: A) Schematic W-E cross sections across the Tampico-Misantla Basin showing its Early Tertiary and Late Tertiary development (Yurewicz et al., 1997). B) Location map of cross sections in A.

Key Findings

Structures located east of the Frio River Line are relatively simple, with a gentle coastward dip and a peripheral belt of normal faults. In contrast, structures located west of this lineament (south Texas, northeast and east Mexico) are more complex and dominated by compressional stresses. The contrasting structural styles should have a different impact on some crucial geotechnical factors of the Eagle Ford Group exploration such as depth of the target, degree of natural fracturing, and geochemical and pressure parameters.

Stratigraphic Framework and Comparison of the Eagle Ford Group in Texas and Equivalent Formations in Mexico

During late Cenomanian-Turonian time, a world-wide marine inundation produced a transgressive cycle which allowed communication between the Gulf of Mexico and the Western Interior Sea. The Eagle Ford Group was deposited in Texas, and similar sediments accumulated in east and northeast Mexico where they have been described with the names of Indidura Formation, Agua Nueva Formation, and Eagle Ford Group (Table 5). The purpose of this section is to discern the stratigraphic similarities and differences among these formations that may have produced a significant impact on the hydrocarbon potential of the hypothetical play in Mexico.

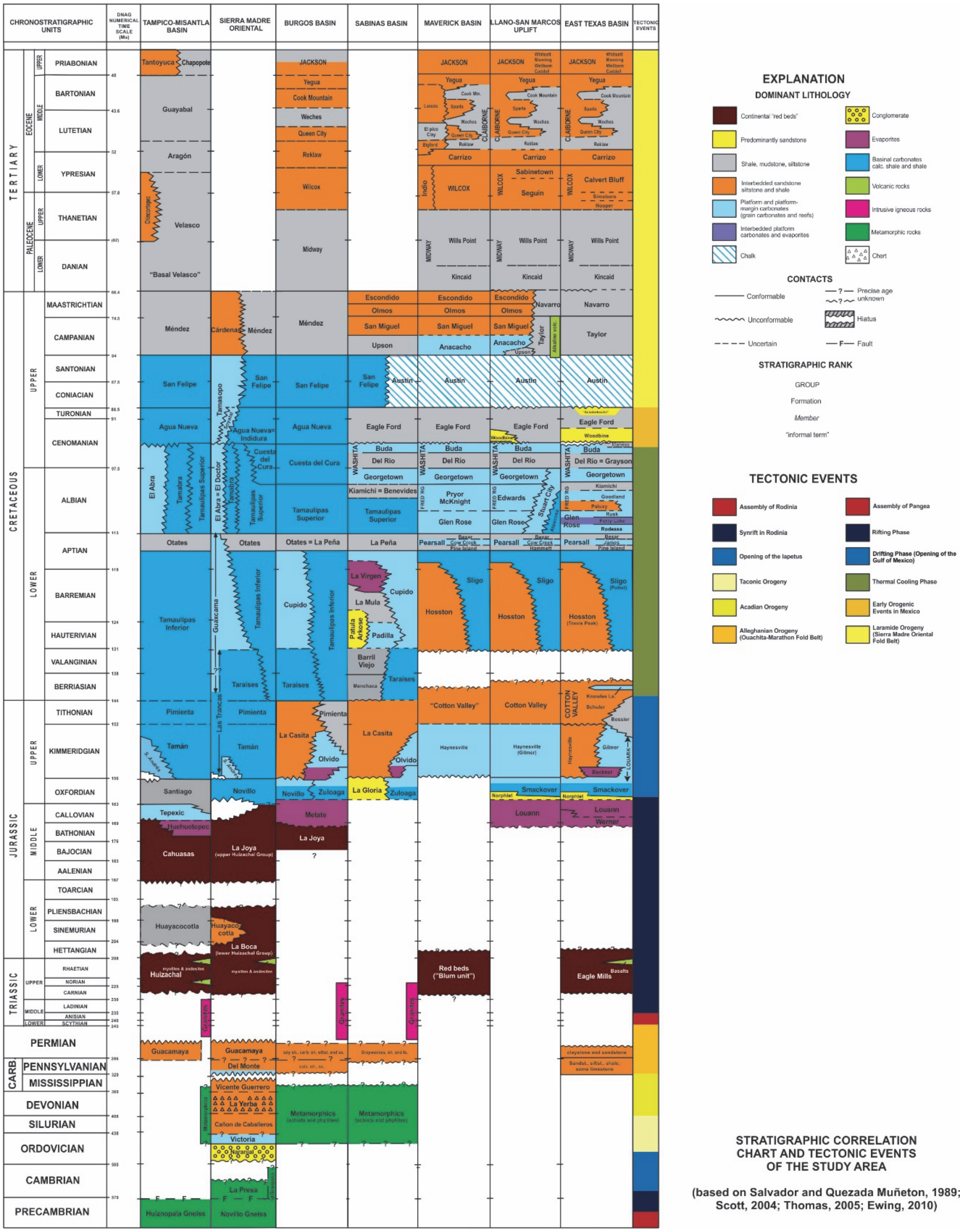


Table 5: Stratigraphic correlation chart of the study area (modified from Salvador and Quezada Muñeton in Salvador, 1991b).

Nomenclature and Distribution (Texas)

In Texas, near the village of Eagle Ford in Dallas County, Hill (1887) used the name of Eagle Ford to describe rocks corresponding to the Late Cenomanian-Turonian that consist of “lustrous, well laminated black shales, which weathers gray to rusty brown.” In this locality, the Eagle Ford Group is underlain by the Woodbine Formation and overlain by the Austin Chalk. South of the Brazos River the Woodbine disappears at the outcrop and the Eagle Ford is underlain by either the Buda Limestone or the Pepper Shale (Adkins, 1928; Dawson and Almon, 2010). After Hill (1887), many geologists, observed that similar rocks in age and lithology extend from the type locality for at over 640 km in a southwest trend through Austin, San Antonio, and the Rio Grande region (Maverick Basin). Along this trend, the rocks display not only lateral and vertical facies changes but also relevant thickness variations across the San Marcos arch (e.g., Udden, 1907; Moreman, 1927; Adkins, 1932). These variations have led some geologists to propose different names to the Eagle Ford Group (Adkins, 1932; Hazzard, 1959; Freeman, 1961; Pessagno, 1966, 1969; Smith, 1981; Trevino, 1988; Donovan and Staerker, 2010). For instance, Udden (1907) described the Boquillas Formation as Late Cenomanian–Turonian strata that crop out in the northwestern flank of the Maverick Basin.

Stratigraphic Relations, Thickness, and Depth (Texas)

In the Interior Zone, the consensus considers the Eagle Ford Group as an unconformably bounded unit. However, Fairbanks (2012) gave evidence of a transitional contact between the Buda Formation and the Eagle Ford Group in a locality next to Austin. The Austin Chalk and Eagle Ford contact represents the Turonian-Coniacian boundary (89 Ma), and the Cenomanian-Turonian boundary (92 Ma) occurs within the Eagle Ford Group (Dawson, 1997). A regional structure contours map made by Hentz and Ruppel (2010, 2011) shows that the Eagle Ford Group extends from “outcrop to just downdip of the Stuart

City and Sligo shelf margins” (~ 4,755 m) (Figure 22). According to these authors, the Eagle Ford Group is thickest in the Maverick Basin and thins over the San Marcos arch (Figure 23). Furthermore, they observe that this Group generally thins downdip “from the Maverick Basin toward and across the Stuart City shelf margin” (Figure 24).

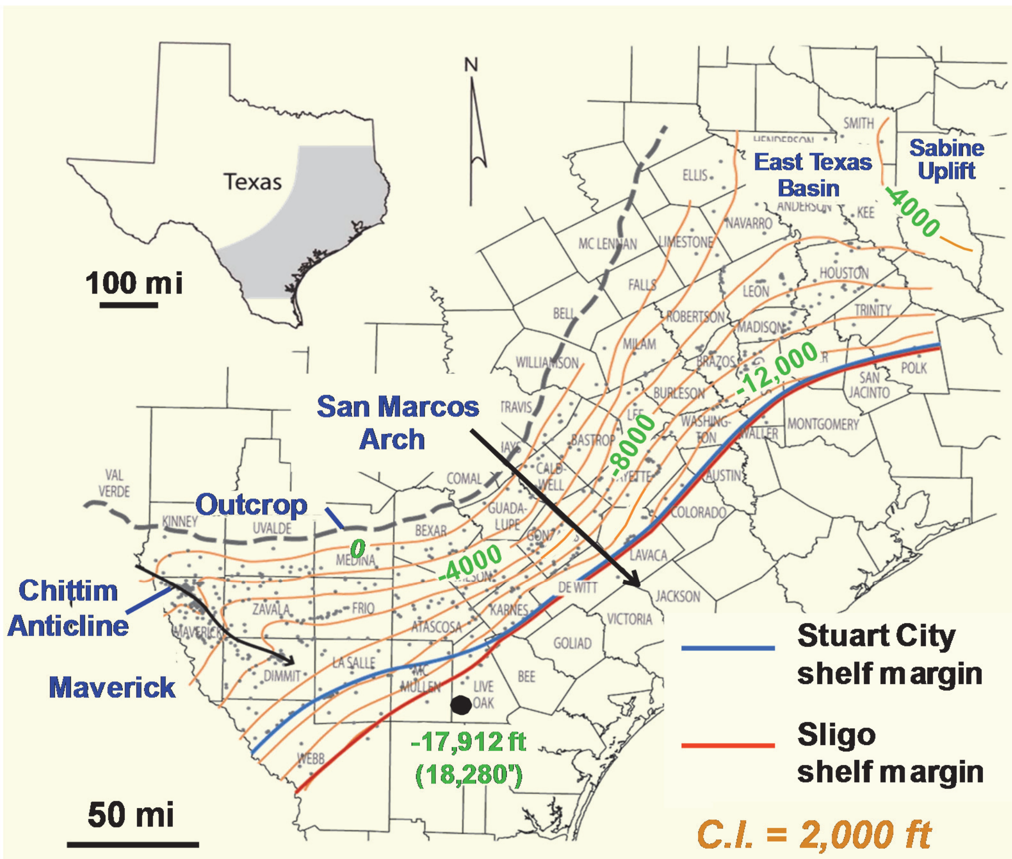


Figure 22: Regional play structure at the top of the Buda limestone (Hentz and Ruppel, 2011)

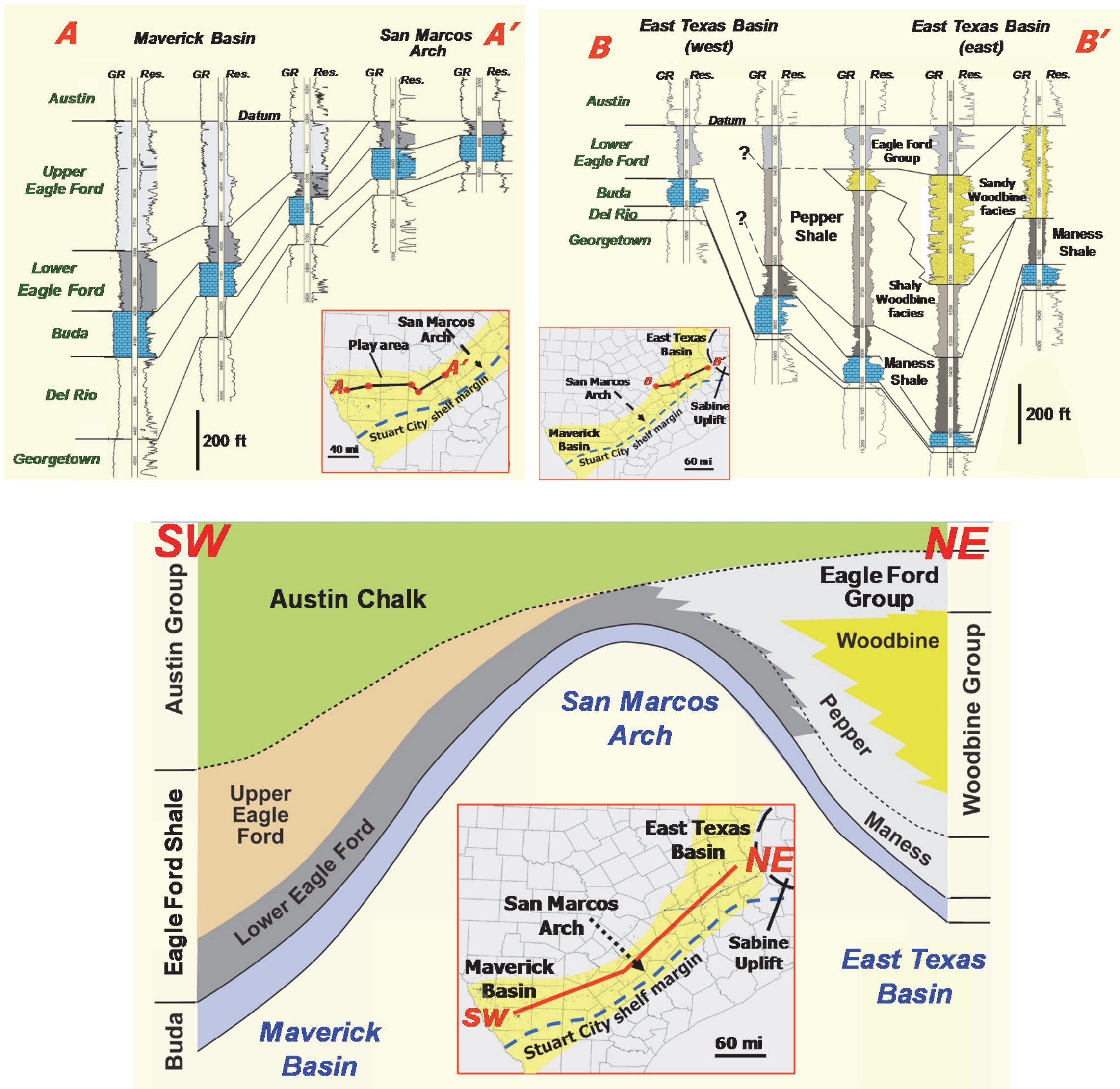


Figure 23: Stratigraphic sections and schematic diagram from the Maverick Basin to the East Texas Basin, showing the stratigraphic relations and thickness of the Eagle Ford play (Hentz and Ruppel, 2011).

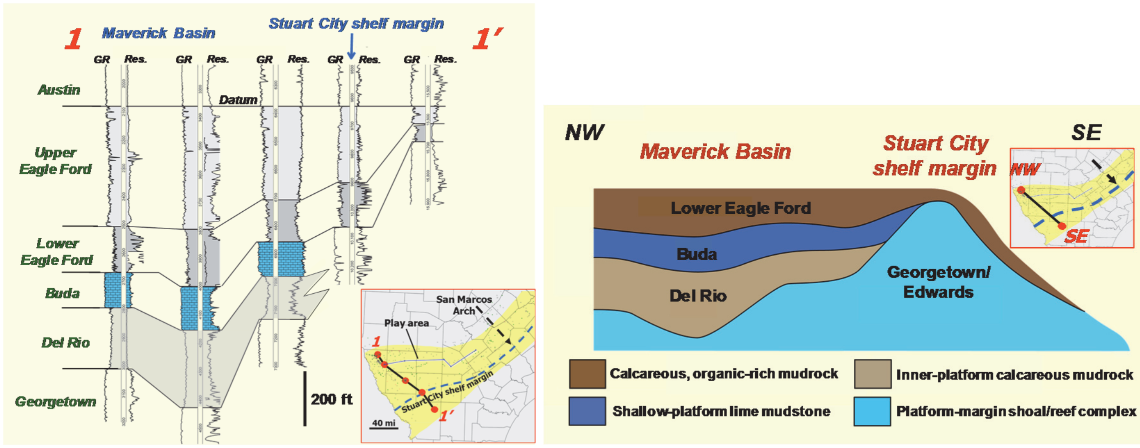


Figure 24: Stratigraphic section and schematic diagram from the Maverick Basin to the Stuart City Shelf Margin showing the stratigraphic relations and thickness of the Eagle Ford play (Hentz and Ruppel, 2011).

Lithology (Texas)

Liro et al. (1994) studied stratigraphic sections in North-Central Texas (Waco-Austin area) and provided evidence that the Late Cenomanian-Turonian Eagle Ford Group was deposited during a major second-order eustatic transgressive interval associated with source-rock deposition. These authors observed that the vertical lithological variability was accompanied by geochemical changes. Thus, the lower unit of the Eagle Ford Group contains organically enriched dark-laminated shales with a few bentonites. The upper unit, exhibits carbonate flagstones, recessive shales, and numerous bentonites. Liro et al. (1994) interpreted the lower unit as a transgressive, organically enriched interval with higher generation potential and more oil-prone than the upper interval which suggest regressive conditions consistent with the onset of a highstand-systems tract.

Of particular economic importance are the regional lateral variations as well. In the Maverick Basin, Hentz and Ruppel (2011) observed that two units characterize the Eagle Ford Group: a lower organic-rich laminated calcareous mud-rock unit and an upper interbedded, burrowed, and laminated calcareous unit. The upper unit pinches out and disappears on the San Marcos arch.

Recently, Dawson (1997, 2000), Lock et al. (2010), Donovan and Staerker (2010) and Donovan et al. (2012) carried out a detailed analysis of geophysical logs, microfacies, and biostratigraphic studies in west and south Texas. Donovan and Staerker (2010) and Donovan et al. (2012) studied outcrops in West Texas where they subdivided the Eagle Ford Group into a Lower Eagle Ford Formation and an Upper Eagle Ford Formation. Each formation in turn was subdivided into two members that display heterogeneous vertical facies with variability in total-organic-carbon. Donovan et al. (2012) considered that the lower Eagle Ford Formation represents a transgressive system track in which mudstone facies are dominant. The upper Eagle Ford Formation represents a highstand system track. The lower Eagle Ford Formation is composed of a lower unnamed member and a Middle Shale Member; whereas the upper Eagle Ford Formation consists of a lower unnamed member and an upper Langtry Member. The four lithostratigraphic members are bounded by regionally mappable unconformities; they are underlain by the Buda Limestone and overlain by the Austin Chalk. At the Lozier Canyon, Donovan and Staerker (2010) identified a vertical succession of 5 facies (A, B, C, D, E) within the two formations (Figure 25).

Donovan et al. (2012) subdivided the 5 facies into sub-facies and interpreted them in terms of system tracks. Sub-facies A to C1 are Cenomanian in age, and the boundary between the Cenomanian and Turonian is near the top of the sub-facies C3. Facies B is "organic-rich calcareous mudstones with scattered limestones interbeds" and contains some of highest TOC values recorded at this site (>4.5%). The base of this facies is interpreted as the maximum flooding surface that culminated the transgressive system track of Facies A. According to Donovan et al. (2012), facies B appears closest in character, as well as similar in stratigraphic position, to the unconventional mudstone reservoirs in the lower Eagle Ford in the subsurface (Figure 26).

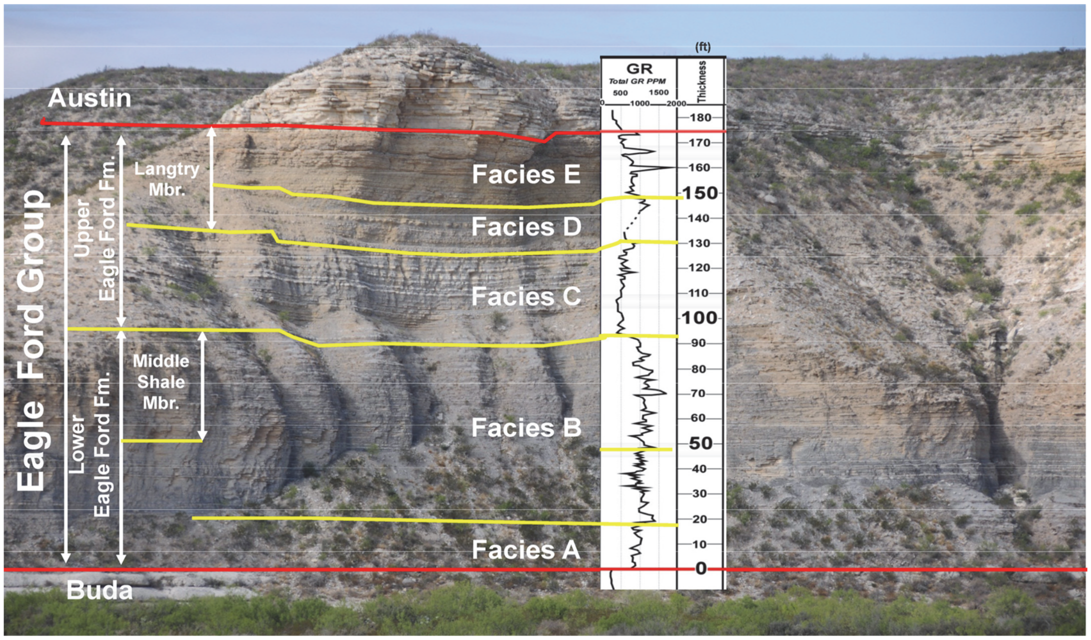


Figure 25: West portion of the Lozier Canyon outcrop face and associated total gamma ray (GR) profile of the measured section (Donovan et al., 2012).

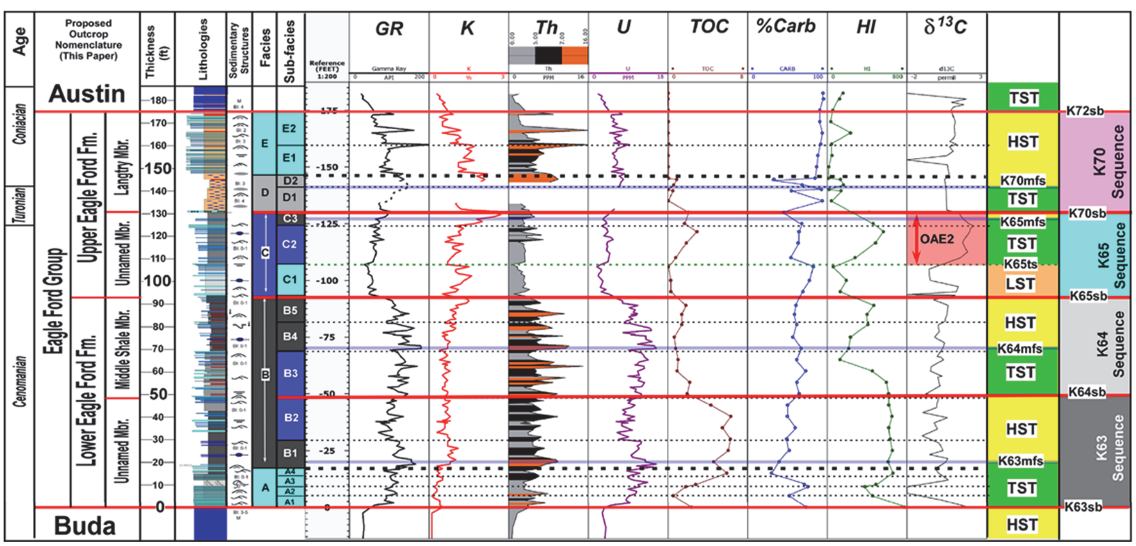


Figure 26: Summary of the lithological, petrophysical, and geochemical data collected in Lozier Canyon in Terrell County, Texas (Donovan et al., 2012).

Nomenclature and Distribution (Mexico)

In Mexico, strata equivalent in age to the Eagle Ford Group are widely distributed and exhibit a more heterogeneous lithology. Conspicuous lateral facies changes were reported in the first reconnaissance surveys (Böse and Cavins, 1927; Burckhardt, 1930). Hence, in the study area, three names have been used to describe the Late Cenomanian–Turonian strata: Eagle Ford Group, Agua Nueva Formation, and Indidura Formation (Kelly, 1936; Muir, 1936; Díaz, 1952). Humphrey (1958) considered that the Monterrey area is critical to observe the facies changes in northeast Mexico (Figure 27). He stated that the Late Cenomanian-Turonian is represented by the Agua Nueva Formation towards east and southeast of Monterrey area; by the Eagle Ford (undifferentiated) towards north and northwest; and by the Indidura Formation toward west and southwest (Figure 27). Humphrey's proposal has not achieved consensus and the name of the Late Cenomanian-Turonian section cropping out along the Front Ranges of the El Burro-Picachos Uplift has been opened to discussion by Díaz (1952), Bishop (1970), and Ifrim and Stinnesback (2008). Díaz (1952) and Ifrim and Stinnesback (2008) described the Late Cenomanian-Turonian with the name of Agua Nueva Formation in the Sierras El Burro, Peyotes, and Vallecillos; while Bishop (1970) gave the name of San Felipe Formation to the section he studied in Sierra de Picachos and Sierra de Papagayos, located to the southwest.

In the regional context provided by Humphrey (1958), the Agua Nueva Formation encompasses the eastern front of the Sierra Madre Oriental, the Sierra de San Carlos and the Sierra de Tamaulipas (Tamaulipas arch), and the Burgos and Tampico-Misantla Basins. The Eagle Ford Group covers the Sabinas and Maverick Basins, and the El Burro-Picachos Uplift. The Indidura Formation is exposed in the Coahuila Platform and in the inner part of the Sierra Madre Oriental foldbelt (Figure 27).

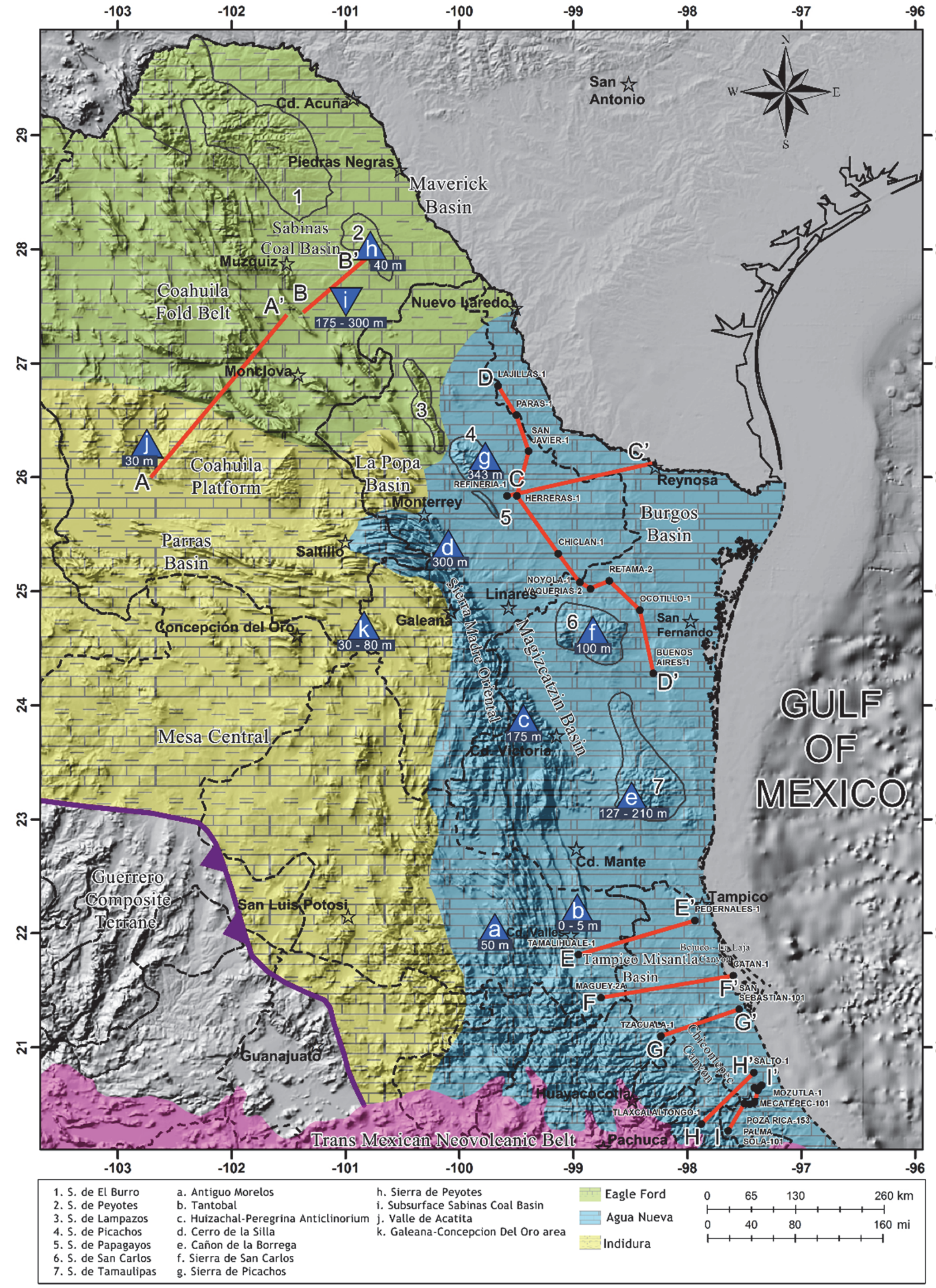


Figure 27: Regional map showing the distribution, thickness, and depth of the Agua Nueva and Indidura Formations, and the Eagle Ford Group in east and northeast Mexico (compiled from different sources mentioned in this text).

Stratigraphic Relations, Thickness, and Depth (Mexico)

In northeast and east Mexico, the stratigraphic relations, thickness, and depth of the Eagle Ford Group, the Agua Nueva and Indidura Formations are highly variable across the basins. Some authors have postulated that these conspicuous changes are due to the irregular paleotopography, paleo-bathymetry, and the influence of the Laramide orogeny (e.g., Muir, 1936; Díaz 1952; Carrillo Bravo, 1961; Longoria y Davila, 1979; Smith, 1986).

In the eastern front of the Sierra Madre Oriental, the Agua Nueva Formation presents two contrasting stratigraphic relationships. On the one hand Smith (1986), observes that over parts of the Valles-San Luis Potosi Platform, the Agua Nueva Formation is very thin and/or is missing (localities a and b in Figure 27, and Figure 28). In contrast, northward, in the Monterrey Curvature this formation is 300 m thick (locality d in Figure 27) and it conformably overlies basinal limestones of the Tamaulipas Superior Formation and conformably underlies the basinal shales and argillaceous limestones of the San Felipe Formation (Longoria and Davila, 1979; Smith, 1986). Between these two areas, in the Huizachal anticlinorium, Carrillo Bravo (1961) observed similar lower and upper conformable contacts in the Agua Nueva Formation and reported an average thickness of 175 m (locality c in Figure 27). Towards the inner part of the Sierra Madre Oriental foldbelt, in La Popa Basin and on the Coahuila Platform, the Indidura Formation conformably overlies the Aurora or the Caracol Formation and in the area of Galeana-Concepcion Del Oro it attains a thickness of 30 m to 80 m (Kelly, 1936, Padilla y Sánchez, 1982; Lawton et al., 2009) (localities k and j in Figure 27).

In the Coahuila Marginal Fold Belt, Salinas E. (1969) reports that the Eagle Ford Group crops out at the flank of twelve anticlines located in western and central part of the foldbelt, where it attains a thickness of approximately 200 m (Figure 27 and cross section

A-A’ in Figure 19A). In these areas, it conformably overlies the Buda Formation and also conformably underlies the Austin Chalk Formation.

In the Front Ranges, surface and seismic information reveal conspicuous changes in thickness of the Upper Cenomanian-Turonian section along some of the mountains (localities e, f, g, and h in Figure 27) (Muir, 1936; Díaz, 1952; Carrillo Bravo, 1961; Bishop, 1970; Perez Cruz, 1993). In these areas, the lower contact of the Agua Nueva Formation or the Eagle Ford Group is conformable with the Tamaulipas Superior, Cuesta del Cura or Buda Formations; while the upper contact is conformable with the San Felipe or Austin Chalk Formations.

In the Tampico-Misantla Basin, four cross sections published by López Ramos (1972) and one by Wilson (1975) indicate that the thickness and depth of the Agua Nueva Formation are highly variable (Figures 27, 29A and 29B, and Table 6). In general, the Upper Cretaceous Agua Nueva Formation dips towards the southwest, crops out in the eastern front of the Sierra Madre Oriental and is absent on the Tuxpan platform (Figure 29A and 29B cross sections E-E’, F-F’, G-G’, H-H’, and I-I’). The influence of the relict Jurassic topography on the thickness of the Upper Cretaceous is observed in the area of the Ebano-Panuco and La Aguada Island (Figure 29A cross sections E-E’ and F-F’). The absence of Upper Cretaceous Agua Nueva Formation on the Tuxpan platform has been observed by several authors (e.g. Sotomayor Castañeda, 1954; Guzmán, 1967; Enos, 1974; Carrillo Bravo, 1980; Janson et al., 2011).

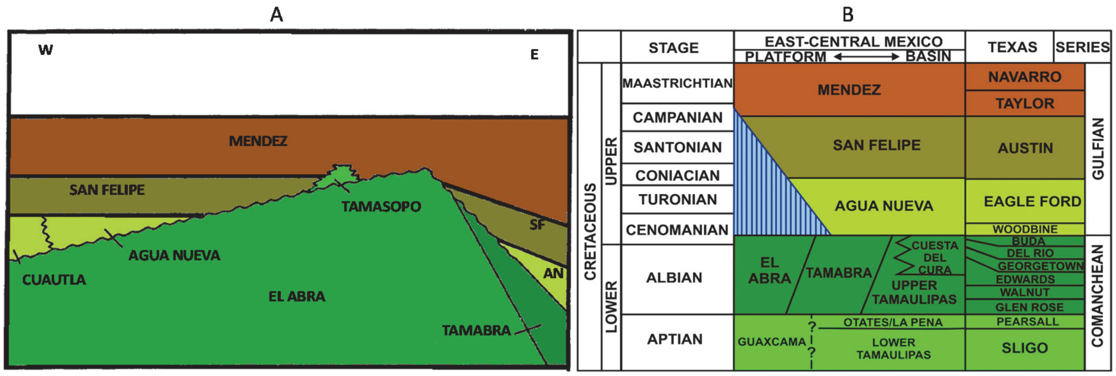


Figure 28: A) Generalized cross section along the eastern edge of the Valles-San Luis Potosi platform, showing the unconformable contact between the Agua Nueva Formation and El Abra Formation (modified from Smith, 1986). B) Stratigraphic chart of East-Central Mexico and Texas showing the middle Cenomanian – Campanian hiatus at the eastern edge of the Valles-San Luis Potosi platform (modified from Smith, 1986).

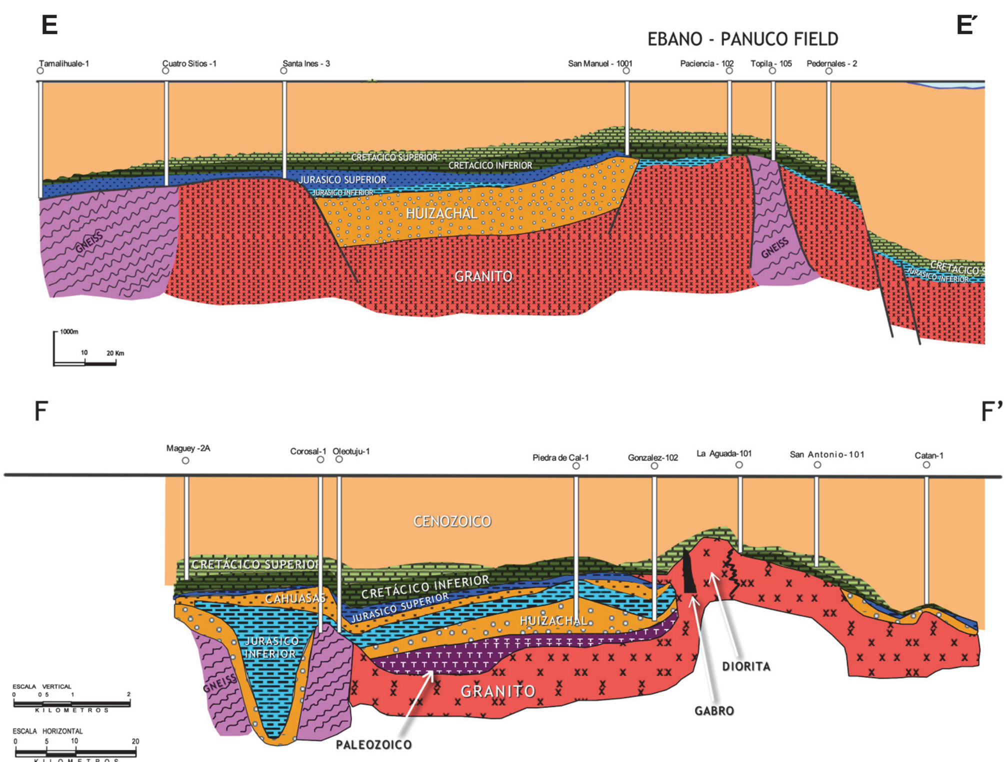


Figure 29A: Schematic SW-NE cross sections across the Tampico-Misantla Basin (modified from López Ramos, 1972). See Figure 27 for the approximate location of these cross sections.

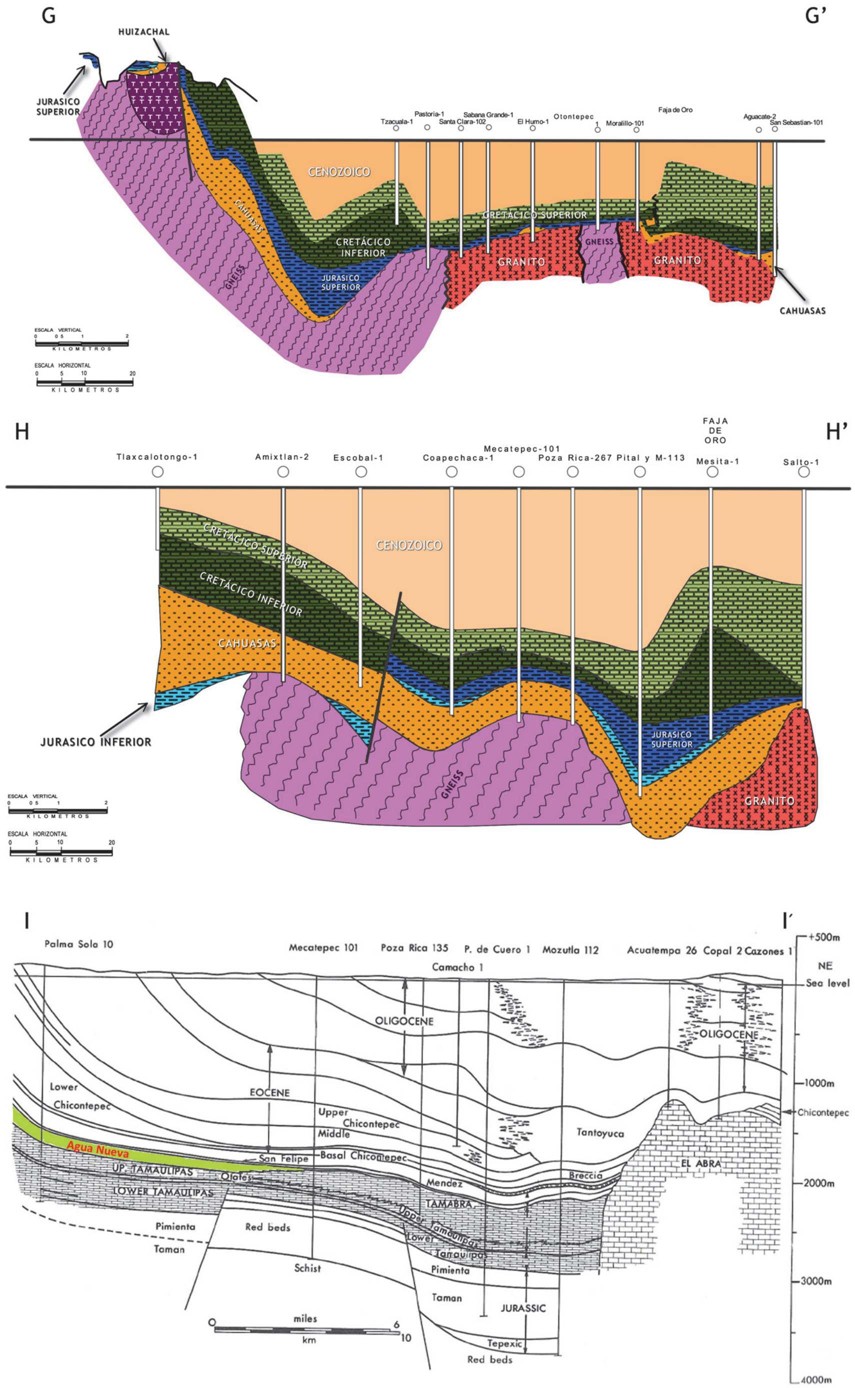


Figure 29B: Schematic SW-NE cross sections across the Tampico-Misantla Basin (modified from López Ramos, 1972; Wilson, 1975). See Figure 27 for the approximate location of these cross sections.

	SW						NE
Cross-section E-E´	**Tamalihuale-1**	**Cuatro Sitios - 1**	**Santa Ines - 3**	**San Manuel - 1001**	**Paciencia - 102**	**Topila - 105**	**Pedernales - 2**
Depth (m)	Absent	1,095	1,068	541	611	931	921
Thickness (m)		105	45	70	64	46	61
Total Depth (m)	2,024	1,743	1,613	1,255	1,261	1,310	1,513

	SW							NE
Cross-section F-F´	**Maguey - 2A**	**Corozal - 1**	**Oleotuju-1**	**Piedra de Cal - 1**	**Gonzalez - 102**	**La Aguada - 101**	**San Antonio - 101**	**Catan- 1**
Depth (m)	1,510	1,523	1,745	Absent	1,284	1,208	1,308	Absent
Thickness (m)	184	105	116		82	108	95	
Total Depth (m)	2,769	2,696	2,975	2,411	2,401	1,396	1,580	2,272

	SW								NE
Cross-section G-G´	**Tzacuala-1**	**Pastoria-1**	**Santa Clara - 102**	**Sabana Grande -1**	**El Humo - 1**	**Otontepec - 1**	**Moralillo - 101**	**Aguacate - 2**	**San Sebastian - 101**
Depth (m)	1,095	1,785	1,705	1,575	1,438	1,280	1,287	944	1,008
Thickness (m)	303	162	198	193	186	175	102	37	50
Total Depth (m)	2,747	2,341	2,622	2,175	2,123	2,060	1,747	2,555	2,978

	SW								NE
Cross-section H-H´	**Tlaxcalaltongo -1**	**Amixtlan - 2**	**Escobal - 1**	**Coapechaca - 1**	**Mecatepec - 101**	**Poza Rica - 267**	**Pital y Mozutla - 113**	**Mesita - 1**	**Salto - 1**
Depth (m)	735	1,090	1,800	1,943	1,906	2,309	Absent	Absent	1,358
Thickness (m)	116	150	205	169	12	40			17
Total Depth (m)	No info.	2,503	2,778	2,778	2,817	2,275	3,791	3,328	2,869

Table 6: Summary of thickness and depth of the Agua Nueva Formation in of some wells depicted in López Ramos (1972) cross sections.

In the Burgos Basin, the Agua Nueva Formation/Eagle Ford Group conformably overlies the Cuesta del Cura Formation, and conformably underlies the San Felipe Formation or the Austin Chalk (Echanove Echanove, 1986). A northwest-southeast cross section presented by Perez Cruz (1993), along the northeastern flank of the Front Ranges upon which the updip limit of the Burgos Basin rests, displays remarkable variations in thickness and depth (Figure 27 and cross section D-D' in Figure 30). Barrios Rivera (2003) interpreted a seismic cross section perpendicular to the one presented by Perez Cruz (1993) (Figure 27 and cross section C-C' in Figure 31). This west-east section, from the Refineria-1 well into the environs of Reynosa shows an east-dipping and thinning of the Upper Cretaceous section. To the east, these strata seem to be at a depth of ~5,000 m below the down - to the - basin growth faults, the Wilcox Fault System.

In the Sabinas Coal Basin, next to the El Burro–Picachos uplift, Robeck et al. (1956) reported that the Eagle Ford Group is at depths ranging between 500 and 600 m with a thickness ranging between 175 and 300 m (Figures 27 and cross section B-B' in Figure 19B). Towards the southwest of this basin, a cross section presented by Eguiluz de Antuñano (2011b) shows that the Eagle Ford deepens to a depth of approximately 2,000 m next to the Oballos anticline.

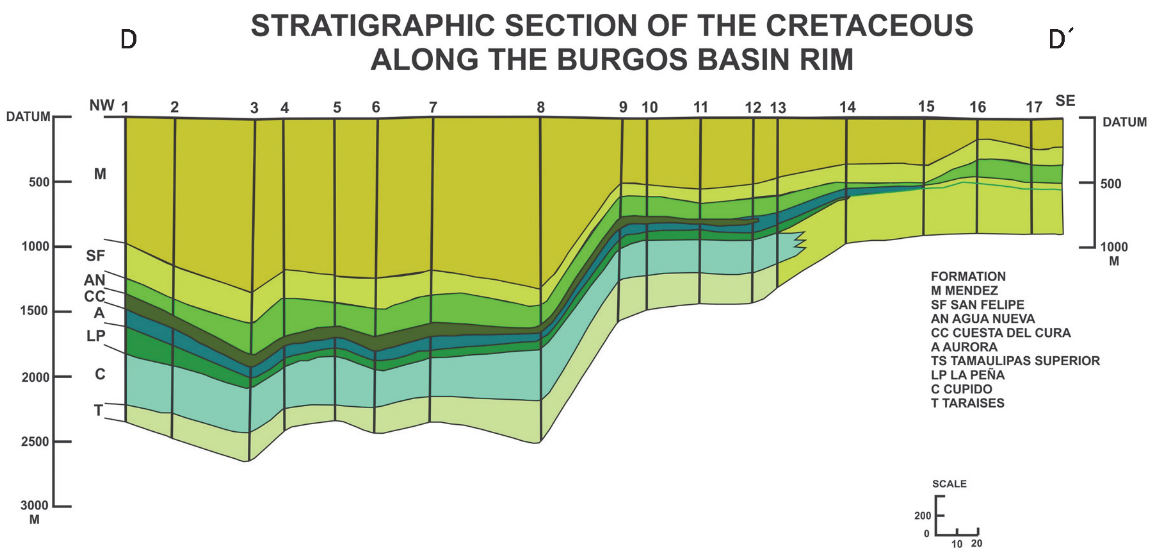


Figure 30: NW-SE stratigraphic section of Cretaceous along the Burgos Basin showing the variation in thickness and depth of the Agua Nueva Formation (modified from Perez Cruz, 1993). See Figure 27 for the approximate location of this cross section.

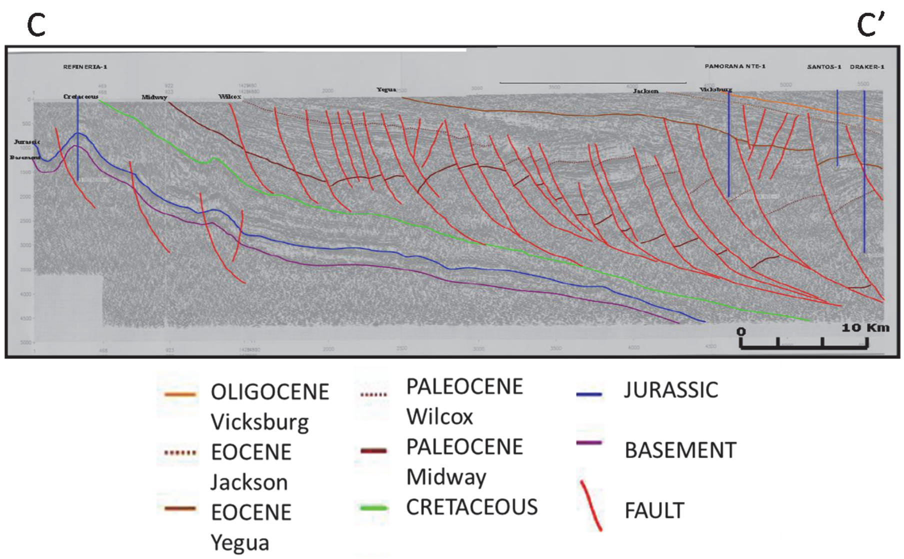


Figure 31: Dip-oriented seismic transect, showing the Mesozoic-Cenozoic structural styles of the Burgos Basin. The Mesozoic strata are folded. The top of the Cretaceous (green line) becomes deeper towards the present Gulf of Mexico Basin. The Cenozoic strata are cut by normal faults dipping basinward (interpretation by Barrios Rivera, 2003). See Figure 27 for the approximate location of this cross section.

Key Findings

In northeast and east Mexico, the stratigraphic relationships, thickness, and depth of the Eagle Ford Group, the Agua Nueva and the Indidura Formations seem to indicate a more complex variability than the Eagle Ford Group in Texas. This difference may have an important impact on the vertical and lateral distribution of the lower organic-rich interval of the late Cenomanian-Turonian section. Therefore, more detailed stratigraphic work is necessary to understand the geological events that controled these three stratigraphic factors critical for shale exploration.

Lithology (Mexico)

In Mexico, recent information concerning to the lithology of the Eagle Ford Group and its equivalent is not public at this time. The following descriptions rely upon classic papers published mainly in Mexican journals. Table 7 displays the lithological and other stratigraphic characteristics of the Agua Nueva and Indidura Formations, and the Eagle Ford Group in northeast and east Mexico.

Formation	Author	Locality	Description
Agua Nueva	Muir (1936)	Sierra de Tamaulipas (Cañon de la Borrega)	200-300 ft of platy chert -bearing limestone's interbedded with black carbonaceous shales
	Sellards (in Muir 1936)	Sierra de Tamaulipas (Cañon de la Borrega)	The lower strata are medium heavy-bedded containing layers of two-thirds meters in thickness, containing relatively little thin-bedded or thin-splitting shaly rock. The middle section becomes distinctly shaly and breaks into thin black layers containing Inoceramus labiatus. The upper most part shows a gradation with the Coniacian. The hard ledges usually from one to two-thirds of a meter in thickness, often alternate with thin layers of shaly thin-breaking rocks.
	Suarez C. (1950)	Western flank of the Golden Lane (Moralillo Field)	Thin bedded carbonaceous limestones with chert interbedded with black shales and bentonites. The upper part is made of well-stratified brown to black limestones with chert and some beds of black shales.
	Carrillo Bravo (1961)	Eastern front of the Sierra Madre Oriental (Huizachal-Peregrina Anticlinorium)	Limestones with black chert nodules and hematite interfingered with white, yellow, and green bentonites. The upper part consists of thin to middle bedded argillaceous limestones, carbonaceous limestones interfingered with black shales.
	Longoria and Davila (1979)	Monterrey Salient of the Sierra Madre Oriental (Cerro de la Silla)	The lower part consists of thin-bedded and laminated argillaceous limestones interbedded with calcareous and carbonaceous shale. In the middle part, the shales gradually disappear and the limestones are laminated and carbonaceous. The upper part consists of thin to thick bedded black limestones with some beds of shales.
	Smith (1986)	Valles-San Luis Potosi Platform	Over parts of this platform, the Agua Nueva Formation unconformably overlies the El Abra Formation. Elsewhere on the platform the Agua Nueva Formation is missing. Thin-to medium-bedded, dark-gray to black, cryptocrystalline limestone with thin interbeds of dark gray shale and bentonite. Faint laminations are common within the limestone. Chert is presented as thin nodules, but is not as abundant as in the underlying Cuesta del Cura Formation.
Indidura	Kelly (1936)	Coahuila Platform (Valle de Acatita)	The lower part is composed of "imperfectly consolidated buff shales containing many crystals of selenite. A thin transitional zone of intercalated platy limestone and shale is included with the Indidura. The highest beds observed are imperfectly stratified buff shales containing numerous veinlets of selenite". Kelly pointed out that the Formation is about 100 feet thick and is divisible in three parts. The lower and upper divisions include the shale beds already mentioned. The middle division consists of interbedded rubbly, gray, pink and red argillaceous limestones, platy limestones, and calcareous shale. Some fossils were collected from the lower division, but they are more numerous in the middle, where there are some fossiliferous horizons. Echinoidea, pelecypods, and cephalopods are the best-represented classes.
	Padilla y Sánchez (1982)	Sierra Madre Oriental (between Linares, Concepcion del Oro, Saltillo, and Monterrey)	A sequence of 30 to 80 m of thin bedded, laminated, wackestone interbedded with shale. This formation is not very fossiliferous and only contains weel preserved shells of Inoceramus labiatus Schlotheim s.l.. The lithology of the Indidura Formation is fairly uniform through all the study area but in the El Sierra del Fraile, west of Gomez Farias, it has thin horizons (1 cm thick) of gypsum and sandstone. This suggests that this formation was probably deposited on a shallow water extensive platform that was gently sloping toward the east, to the deeper water in which the Agua Nueva Formation was deposited.
Eagle Ford Mexico	Díaz (1952)	El Burro-Picachos uplift (Sierra de Peyotes)	The lower part consists of 5 m of thin-bedded and laminated black argillaceous limestone and calcareous shale. The middle part is made up of 20 m of brown to black laminar shale with some beds of argillaceous limestone. The upper schist consists of 10 m of bentonitic shale and thin-bedded black limestone.
	Humphrey and Díaz (1956)	Sabinas Basin - Coahuila Marginal Fold Belt (Sierra de la Gavia)	A lower unit composed of black, carbonaceous, and calcareous laminated shale. An upper unit made up of black and gray laminated shale interbedded with thin and laminated black limestone with Inoceramus labiatus.
	Bishop (1970)	El Burros-Picachos uplift (Sierras de Picachos and Papagayos)	Monotonous sequence of interbedded clayey limestones, shale, and calcareous claystone. The clayey limestones are thin, evenly bedded, mottled and burrowed and do not contain chert. They weathered into rectangular blocks or slabs. The calcareous claystones are thin bedded and interfingered with brown shale. They contain Globigerina and fragments of Inoceramus. The calcareous claystones constitute the upper most part of the formation. Bishop believes that this unit should be named San Felipe Formation.

Table 7: Lithological characteristics of the Agua Nueva and Indidura Formations, and the Eagle Ford Group in east and northeast Mexico.

Key Findings

1- Most authors consider that the Agua Nueva Formation can be subdivided into two or three vertical facies. In general, they have observed that the lower part is characterized by thin-bedded carbonaceous limestones with nodules of chert and beds of bentonite, interbedded with laminar shales. Upward the section becomes distinctly shaly and contains Inoceramus labiatus, and the upper part is made up of limestones and some beds of shales. Therefore, it is possible to infer that the lower section may correlate with the organic-rich interval of the Eagle Ford Group in Texas; but detailed stratigraphic and geochemistry works are necessary to prove it.

2- The Eagle Ford Group can be subdivided into two or three vertical facies as well. The lower section consists of thin-bedded and laminated black argillaceous limestone and calcareous shales. The middle is made up of brown to black laminar shales with some beds of argillaceous limestones. The upper part is black and gray, laminated shales interbedded with thin and laminated black limestones with Inoceramus labiatus. Probably the main difference with the Agua Nueva Formation is that it is more argillaceous and does not contain chert in the lower part. A sequence stratigraphic approach and geochemistry studies are necessary to understand a correlation with the lower organic-rich interval of the Eagle Ford Group of Texas.

3- The wackestones interbedded with shales with some Echinoidea, pelecypods, cephalopods, some shells of Inoceramus labiatus, and thin horizons of gypsum and sandstones (Sierra del Fraile) of the Indidura Formation, probably were deposited on an eastward gently sloping shallow-water platform towards deeper water deposits, corresponding to Agua Nueva Formation (Padilla and Sanchez, 1982). In comparison with the Agua Nueva Formation and the Eagle Ford Group, the

Indidura Formation displays a greater influx of argillaceous sediments. This feature and its shallower marine environment of deposition suggest conditions leading to poor preservation of organic matter.

REGIONAL PALEOGEOGRAPHIC CONTEXT

Two main geological differences between the Eagle Ford Group of Texas and their equivalent formations in east and northeast Mexico were observed: 1) different structural settings, 2) heterogeneous lithology, variable stratigraphic relations, and lateral and vertical changes in thickness and depth are more conspicuous in east and northeast Mexico than in Texas.

In order to understand the possible implications of these two differences in the exploration phase of this hypothetical play in Mexico, it is crucial to identify the geological factors that produced these differences within a Mesozoic-Early Cenozoic paleogeographic and tectonic evolution context of the study area. This work distills salient aspects of the regional analysis made by Padilla y Sánchez (1982), Smith (1981), Salvador (1987, 1991a, 1991c), Wilson (1990), Goldhammer and Wilson (1991), Goldhammer and Lehmann (1991), Goldhammer (1999), Dickinson and Lawton (2001), and Goldhammer and Johnson (2001).

The assembly of Pangea. Earliest Permian 281 Ma – Middle Triassic 232 Ma.

Dickinson and Lawton (2001) proposed an Early Permian–Middle Triassic tectonic reconstruction of Pangea in which the Llano-San Marcos uplift is the only Laurentian element of the study area and it delineated the southeastern margin of Laurentia (Figure 32). According to these authors, the metasedimentary Upper Paleozoic rocks of the Front Ranges and the Coahuila platform represent the collision between the Gondwana blocks and Laurentia; while the Late Permian-Middle Triassic granitic rocks that intrude these rocks represent a continental arch related to the subduction of the Pacific Plate.

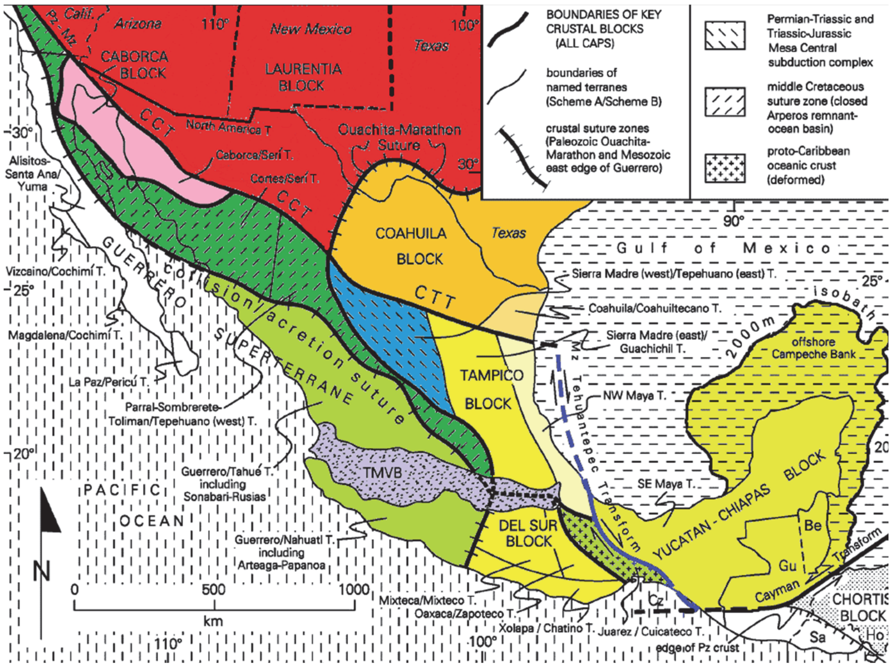


Figure 32: Distribution and names of key Early Permian–Middle Triassic crustal blocks (redrawn from Dickinson and Lawton, 2001).

Rifting Phase. Late Triassic 237 Ma - Middle Jurassic (Callovian) 164 Ma.

The rifting phase that took place in the proto-Gulf of Mexico during the Late Triassic-Middle Jurassic was the product of tensional stresses which were triggered when the Yucatan continental block and the South American plate began their southward drift away from the remaining of the North American plate (Salvador, 1987, 1991c; Goldhammer and Wilson, 1991; Goldhammer and Johnson, 2001). Thus, rift tectonics gave rise to grabens in the present areas of the Tampico-Misantla, Sabinas, Maverick and East Texas Basins, where red beds were deposited as the product of the erosion of the high-standing blocks (Figure 33).

During the Bathonian-Callovian and Early Oxfordian, the sea water from the Pacific embayment combined with restricted conditions and an arid climate resulted in the deposition of the extensive and thick evaporites of the Werner Anhydrite and Louann Salt Formations in the proto-Gulf of Mexico According to Salvador (1987, 1991a, 1991c) (Figure 34). Salvador (1991c) states that the shallow hypersaline basin was terminated by sea floor-spreading and the emplacement of oceanic crust. The mid/oceanic ridge system split the Callovian salt basin into two separate salt provinces (Salvador, 1987, 1991a, 1991c).

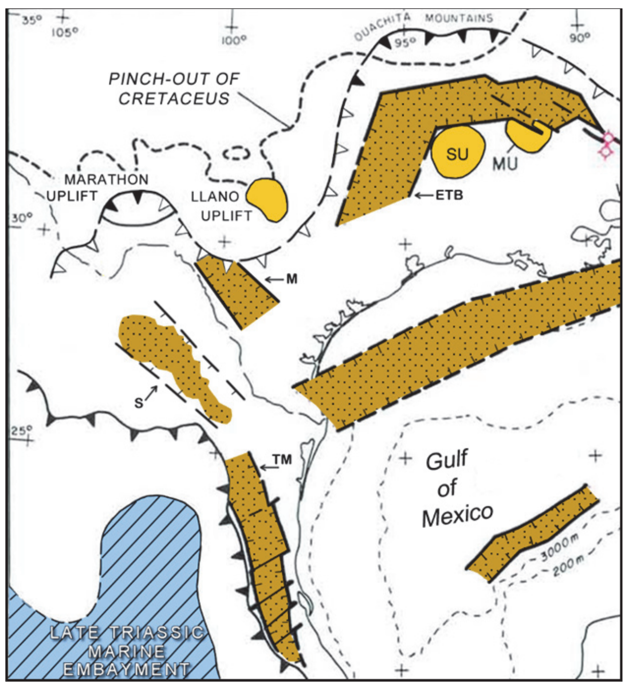


Figure 33: Distribution of Late Triassic- Early Jurassic grabens filled with red beds in the Gulf of Mexico Basin (modified from Salvador, 1991a). MU= Monroe uplift; SU= Sabine uplift; ETB= East Texas Basin; M=Maverick Basin; S= Sabinas Basin; TM=Tampico-Misantla Basin

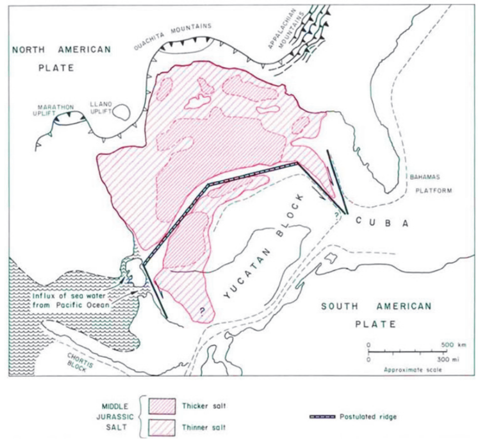


Figure 34: Distribution of salt deposits during the late-Middle Jurassic (Salvador, 1991a).

Drifting Phase. Late Jurassic (Middle Oxfordian) 159 Ma – Tithonian 139 Ma.

The conclusion of the rifting phase in the proto-Gulf of Mexico Basin was followed by the southward drift of the Yucatan block into its present position along left-lateral transform faults located at the eastern margin of the Tamaulipas arch and at the western margin of the Florida platform (Salvador, 1987, 1991c; Goldhammer and Wilson, 1991; Goldhammer and Johnson, 2001; Hammes et al., 2011). This motion produced the first difference in the tectonic and paleogeographic evolution between the Interior Zone and the Western Compressional Zone. The Western Compressional Zone became a transform margin that broke up the Tamaulipas arch; while the Interior Zone evolved into a passive margin subject to the first vertical movement of the salt as it began to receive sediment loading.

By Late Oxfordian-Kimmeridgian, the marine waters encroached upon east and northeast Mexico, as well as in the Texas coastal zone (Salvador, 1987, 1991c; Goldhammer and Wilson, 1991; Goldhammer and Johnson, 2001) (Figure 35 and 36). Thus, a broad carbonate ramp sloping gently towards the center of the Gulf of Mexico Basin was established in which oolitic shoals were deposited updip and basinal carbonates and shaly deposits accumulated basinward. The Coahuila platform and the El Burro-Picachos uplift became peninsulas and the source of terrigenous and in the Early Kimmeridgian the oolitic shoals extended southward and straddled on the islands of the Tamaulipas arch.

According to Salvador (1991a, 1991c) a widespread marine transgression returned during the Late Kimmeridgian and the evaporitic deposits were covered by carbonate sediments. During the Tithonian, transgression reached its peak and the waters of the Gulf of Mexico of the time covered most of the islands of the Tamaulipas arch and only small areas of the Coahuila platform, the Valles San –Luis Potosi platform and of the El Burro uplift were exposed and provided siliciclastics to the margins of the basin (Figure 37).

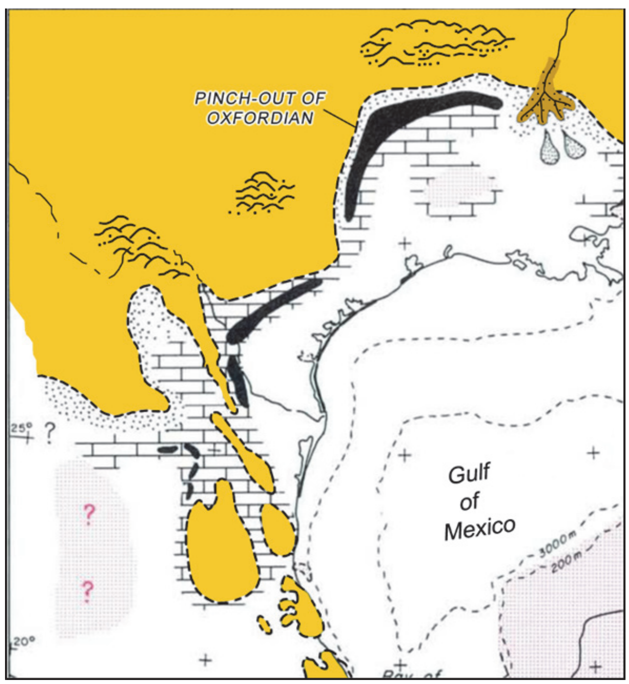


Figure 35. Paleogeography of the study area during the late Oxfordian (modified from Salvador, 1991a).

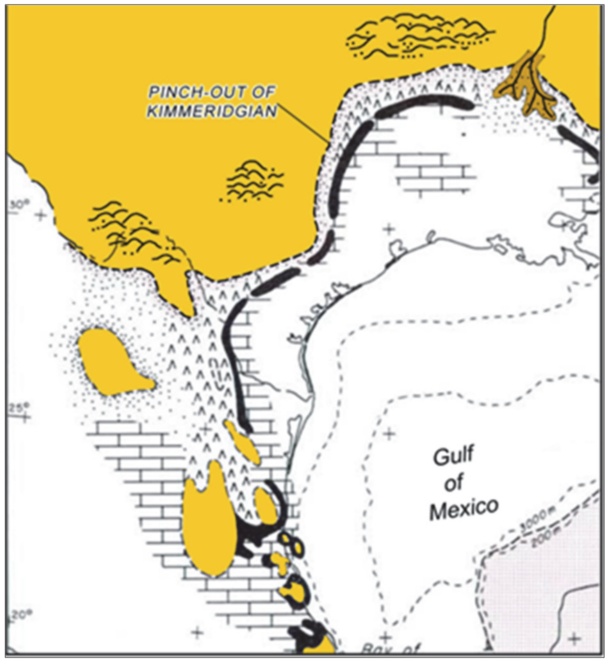


Figure 36: Paleography of the study area during the early Kimmeridgian (modified from Salvador, 1991a).

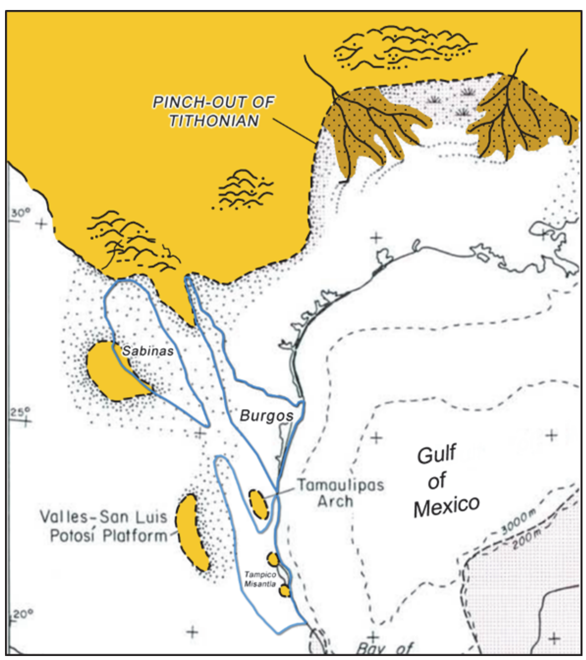


Figure 37: Paleogeography of the study area during the late Tithonian (modified from Salvador, 1991a)

Thermal Cooling Phase. Early Cretaceous (Berriasian) 145 Ma – Late Cenomanian 93.9 Ma.

At the beginning of the Early Cretaceous, the opening of the Gulf of Mexico was completed. Consequently, the shear margin that existed in the Western Compressional Zone became a passive margin. Thus, the Western Compressional Zone and the Interior Zone are passive margins where subsidence was controlled by the combined effects of thermal cooling and sediment loading (Goldhammer and Wilson, 1991).

During the Berriasian-Valanginian, the Interior Zone was the site of an extensive carbonate platform bordered by the Llano-San Marcos uplift, El Burro-Picachos uplift, and the Coahuila platform that were the source of clastics that gradually changed downdip into carbonates deposited in shelfas areas. Meanwhile, in the Western Compressional Zone the ancient positive blocks of igneous and metamorphic rocks controlled the position of isolated carbonate platforms surrounded by deep-water carbonates (the Valle-San Luis Potosi and the Tuxpan platforms) (Wilson and Ward, 1993) (Figure 38).

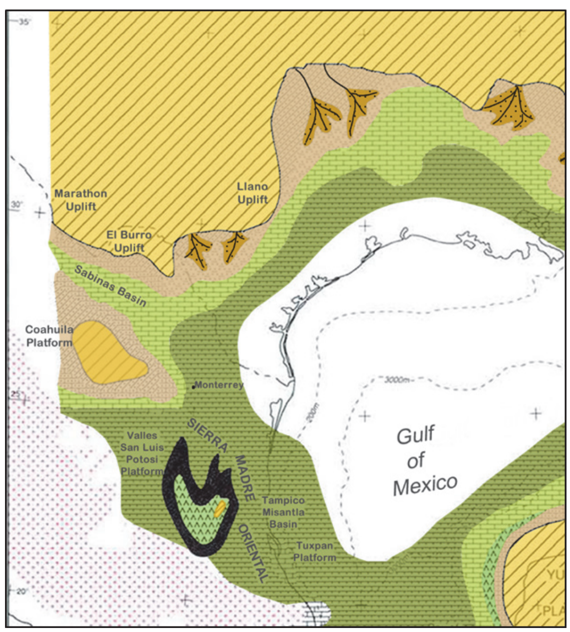


Figure 38: Paleogeography of the study area during the Berriasian-Valanginian (modified from McFarlan and Menes, 1991)

By Barremian time, in the Interior Zone, a transgressive event led to a general overlap of the terrigenous clastics and the establishment of a widespread carbonate platform with a reef-rimmed shelf margin of low-relief that covered most of the area located between the Sabine uplift and the Coahuila platform (Sligo-Cupido shelf margin) (Figure 39). In the platform, interior muddy lagoonal carbonates and tidal flat facies were deposited, and in the basin mudstones and shales (McFarlan and Menes, 1991; Goldhammer, 1999). By Early Aptian, the Sligo-Cupido Formations attained their maximum development, and a well-defined platform margin extended from Texas, south of Laredo to Monterrey (Smith, 1981; Salvador, 1991a). In the Western Compressional Zone, rudist reef rimmed platforms (Valles-San Luis Potosi and Tuxpan Platforms) remained surrounding lagoons filled with evaporites (Viniegra and Castillo-Tejero, 1970; Carrillo-Bravo, 1971; Pedrazzini, 1978; Wilson and Ward, 1993; Goldhammer and Johnson, 2001).

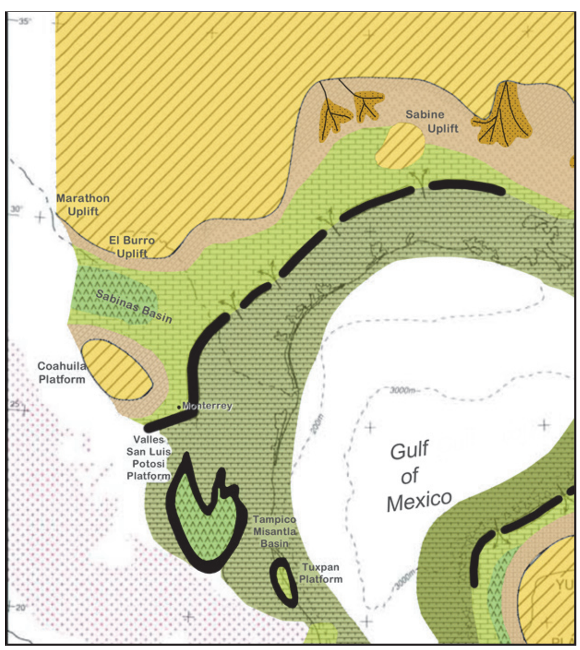


Figure 39: Paleogeography of the study area during the Barremian – Early Aptian (modified from McFarlan and Menes, 1991).

In Late Aptian, an episode of sea-level rise (Scott et al., 1988; Goldhammer and Johnson, 2001) coincides with the input of large volumes of fine-grained terrigenous material into the northern and southern domains (Smith, 1981; Salvador, 1991a). This episode terminated the deposition of the Cupido-Sligo platform and diminished the size of the Valles-San Luis and Tuxpan platforms. (McFarlan and Menes, 1991; Goldhammer and Johnson, 2001) (Figure 40).

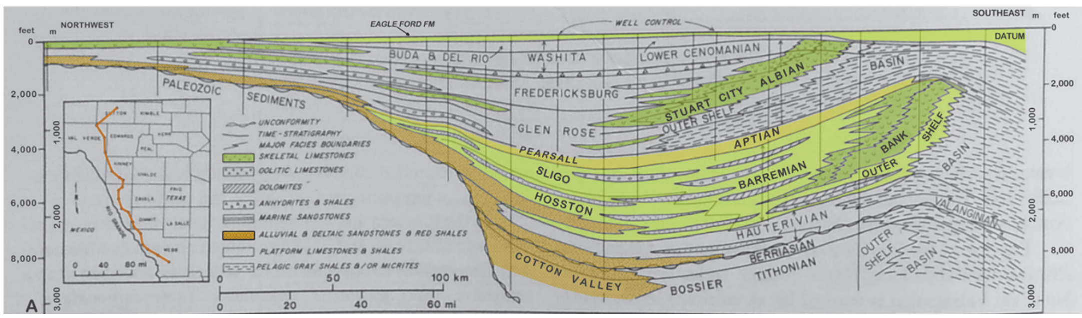


Figure 40: Generalized regional dip section of Lower Cretaceous deposits across South Texas, showing the distribution of the deep-water deposits of the Pearsall - La Peña – Otates Formations that inundated the carbonate platform (modified from McFarlan and Menes, 1991).

During the Albian, the shelf carbonate deposition was re-established in the Interior Zone. The morphology of this shelf, as well as the differential subsidence that took place during this time, have an important influence on some stratigraphic characteristics of the Eagle Ford Group. This shelf extended in northern Coahuila, and central and southwest Texas (Fisher and Rodda, 1969; Barcelo-Duarte, 1983) and was limited to the northeast and southeast by two depressions: the Maverick Basin (Winter, 1961) and the Tyler Basin (East Texas Basin) (Rose, 1972), respectively (Figure 41). Differential subsidence resulted in fault motions that formed a narrow system of synthetic and antithetic en echelon faults known as the Karnes and the Atascosa Troughs at the southern part of the Llano-San

Marcos uplift (Eargle, 1959; Tucker, 1968; Rose, 1972). Thus, carbonate facies were deposited on the shelf that was centered on the Llano-San Marcos uplift and evaporites and platform interior carbonates in the Maverick Basin (Rose, 1972).

Gulfward, the Stuart City reef trend developed along the platform margin, and basinward thin-bedded limestones and marls were deposited (McFarland and Menes, 1991). The Stuart City trend expanded into northeast Mexico along the subsiding southwestern rim of El Burro uplift (Smith, 1981) and encircled the Maverick Basin. Thus, the Albian differential subsidence led to the Sabinas Basin to be a deep-water depocenter that separated the Coahuila platform from the Maverick Basin platform. The lime argillaceous limestones of the Tamaulipas Superior Formation deposited in the Sabinas Basin and extended into the southern domain and encircled the offshore carbonate banks (Wilson, 1975; Lehman et al., 1999) (Figure 41).

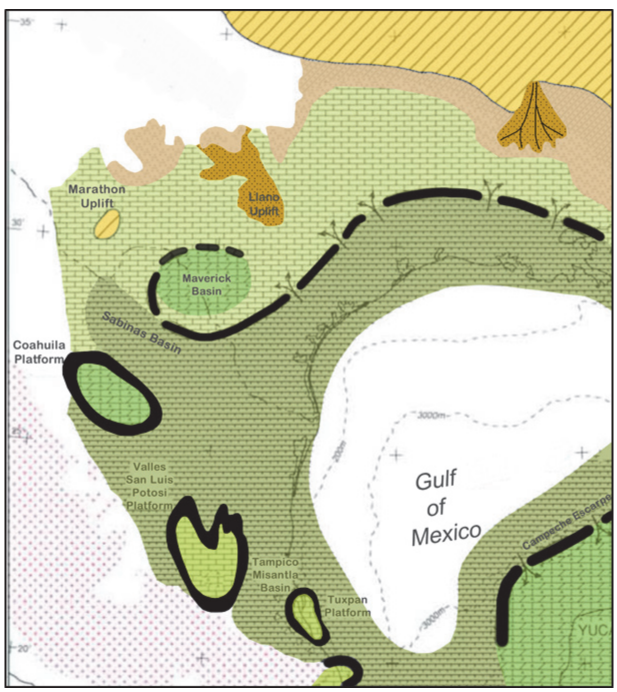


Figure 41: Paleogeography of the study area during the Albian- Early Cenomanian (modified from McFarlan and Menes, 1991).

In Late Albian-Early Cenomanian continued subsidence combined with high eustatic sea levels caused the platforms to drown and step back (Li and Buffler, 1997). The Georgetown and Salmon Peak Formations filled in the paleotopography, and then clays and lime mudstones (Del Rio and Buda Formation, respectively) blanked the entire area (Rose, 1972).

In the Gulf of Mexico, the Middle Cenomanian worldwide sea-level fall reported by Vail et al. (1977) caused a stratigraphic break of regional extent in the Comanche platform as well as in the offshore carbonate banks of the northeast and east Mexico (Stephenson, 1927, 1929; Smith, 1986; Salvador, 1991a; Eguiluz de Antuñano, 1991) (Table 8). Thus, the Tuxpan, Valles-San Luis Potosi, and Coahuila platforms underwent subaerial erosion (Sotomayor Castañeda, 1954; Guzmán, 1967; Sansores Manzanilla and Girard Navarrete, 1969; Enos, 1974; Smith, 1986; Eguiluz de Antuñano, 1991; Janson et al., 2011).

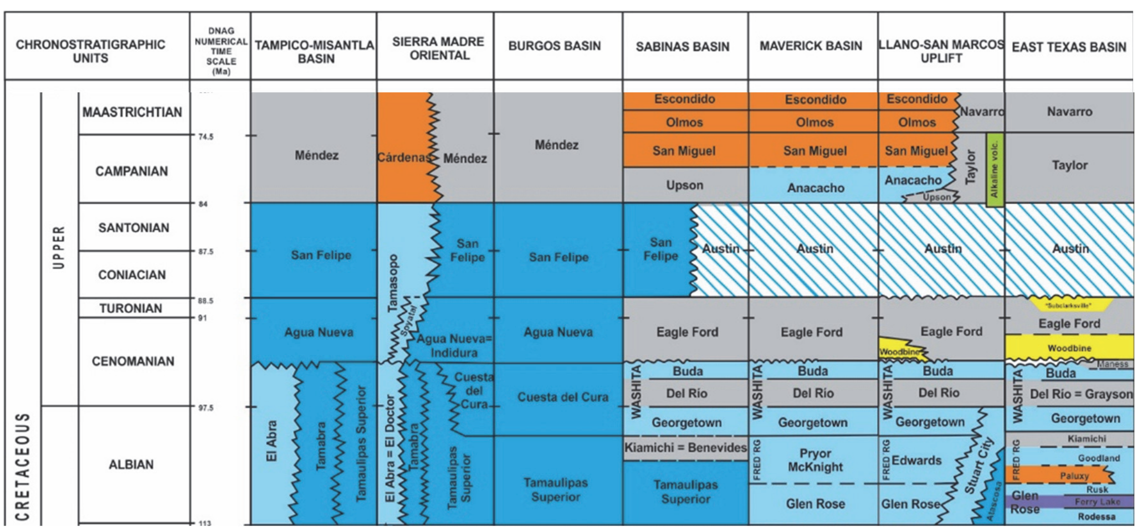


Table 8: Stratigraphic table of the study area showing the distribution of the Middle Cenomanian unconformity (modified from Salvador and Quezada Muñeton, 1989 in Salvador 1991b).

The Great Marine Transgression and Early Orogenic Events in Mexico - The Deposition of the Eagle Ford Group. Late Cenomanian 93.9 Ma - Turonian 89.8 Ma.

The Middle Cenomanian sea-level fall was followed by a major marine transgression correlative with worldwide sea-level rise (Vail et al., 1977), which along with thermal cooling subsidence and sediment loading were the first-order controls on the Late Cenomanian-Turonian sedimentation. Schlanger and Jenkins (1976) and Schlander et al. (1987) observed that during this time, organic carbon-rich sediments were globally developed and interpreted this fact as the product of "Oceanic Anoxic Events" which resulted from the interplay between tectonics and climatic conditions (Figure 42). A pulse of rapid seafloor spreading increased the volume of the mid-ocean ridge system that in turn led to the major transgression; and mild and equable period of climate reduced the amount of oxygenated sinking cold water provided by the higher latitudes (Schlanger and Jenkins, 1976). According to Hallam (1977), the Late Cretaceous was, except at the end, a period when tropical-subtropical climate extended to at least 45° C and warm to cool temperature climate extending to the poles. This transgression led to the communication of the Gulf of Mexico Basin with the Interior Sea of North America.

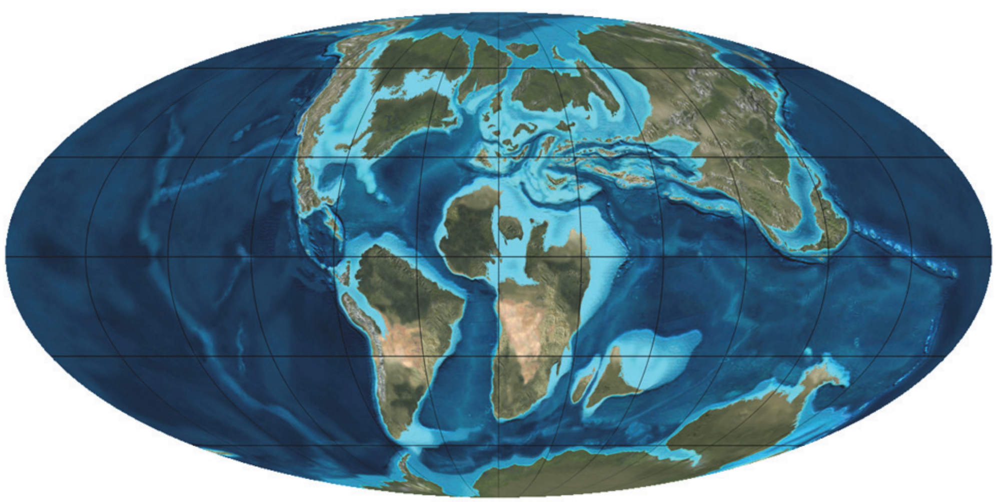


Figure 42: Turonian paleogeographic map of the world showing the major transgression that led to the deposition of organic carbon-rich sediments (Blakey, 2015).

In Texas, as well as in east and northeast Mexico, accommodation was generated by thermal cooling, sediment loading, and sea-level rise. In addition, an irregular topographic relief caused by the presence of the Llano-San Marcos uplift, the synsedimentary upwarping motion of the Sabinas uplift, and the differential subsidence produced the Maverick Basin and the Karnes Trough (Figure 43).

In northeast and east Mexico, some lines of evidence suggest that differential subsidence and upwarping of some regions were produced by a tectonic deformation that seems to indicate an early phase of the Laramide orogeny. In contrast to Texas, the uneven relief was enhanced by the initial deformation of the Sierra Madre Oriental and the reactivation of old weakness zones along the margins of ancient basement uplifts.

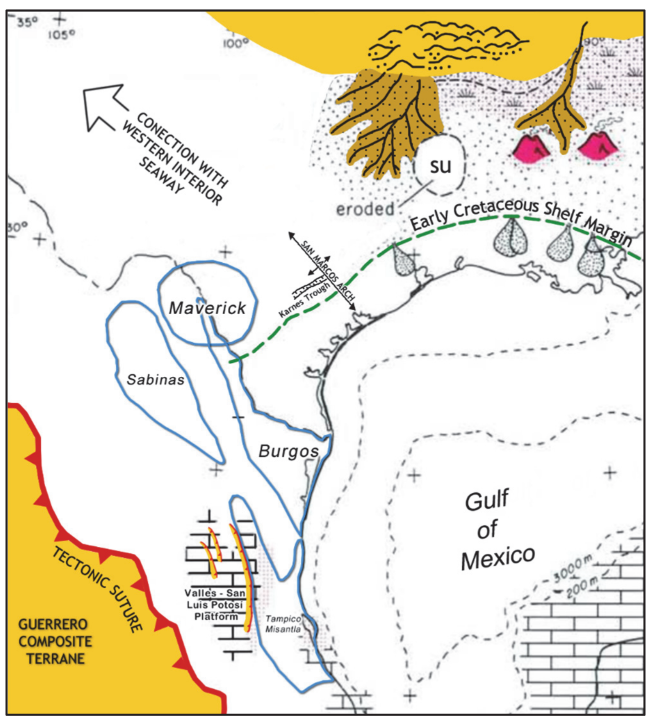


Figure 43: Paleogeography of the study area during the Late Cenomanian-Turonian when the transgressive event was coeval with the accretion of the Guerrero Composite Terrane and uplift in the Valles-San Luis Potosi Platform (modified from Salvador, 1991a).

A few authors have reported a middle-Late Cenomanian deformation in Mexico. Alvarez (1962) proposed the existence of the “Orógeno Cenomaniano” on the basis of the great amount of granites of this age in Western Mexico. Muir (1936), Suarez C. (1950), Millison (1953), and Sánchez López (1954) suggest a middle Cenomanian tectonic motion in Mexico on the basis of the thickness variations of the Agua Nueva Formation observed in the Tampico-Misantla Basin and the presence of bentonite layers at the base of the Agua Nueva Formation. Smith (1986) gave evidence to propose that this deformation caused folding, faulting and uplift of the Valles-San Luis Potosi platform, and suggested that it is contemporaneous with the Cenomanian orogeny reported by Wilson (1974) in Central America. Another piece of evidence of tectonism is the influx of argillaceous sediments terrigenous into the Gulf of Mexico Basin that started in the Middle Cenomanian and continued through the Late Cretaceous (Smith, 1986). Recently, Centeno-Garcia et al. (2008) proposed that by Cenomanian?– Pre-Santonian, the initial accretion of the Guerrero composite terrane, produced granitic intrusions in southern Mexico, folding and thrusting in Central Mexico, and syntectonic marine turbidites in central and eastern Mexico (Figure 44).

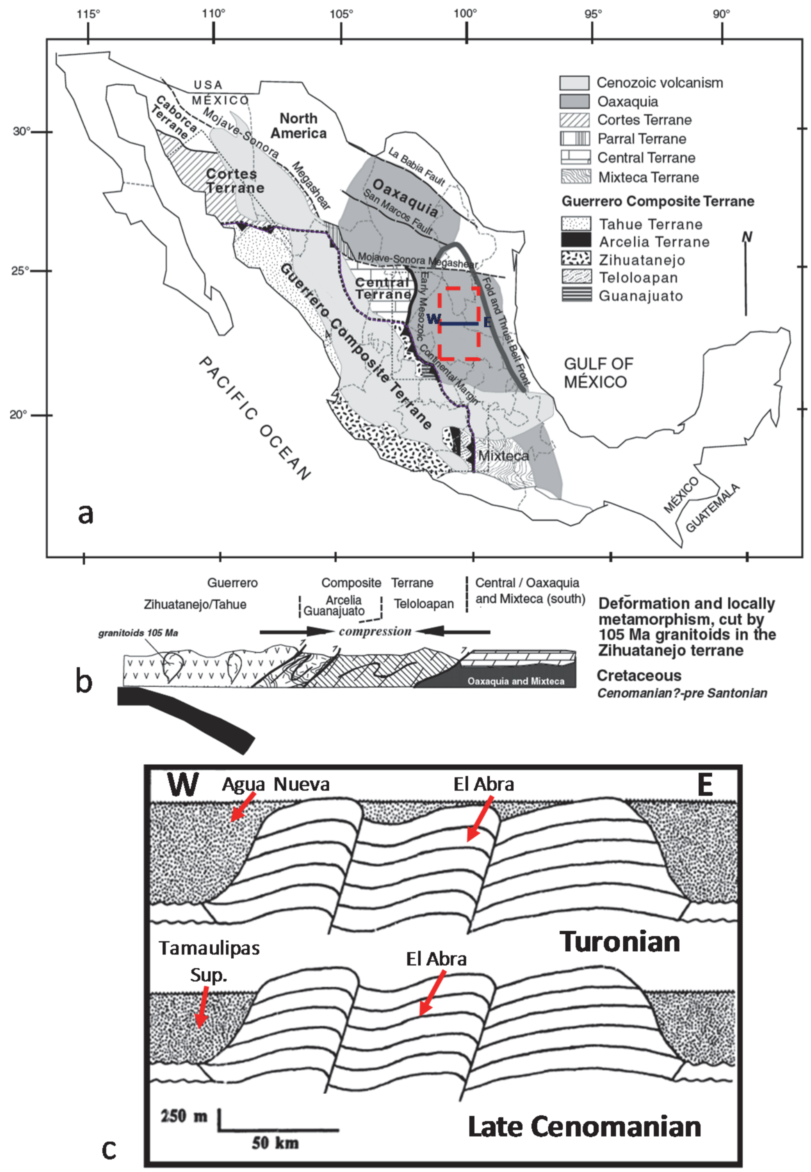


Figure 44: A) Map showing the location of the tectonic suture produced by the accretion of the Guerrero Composite Terrane over eastern and southern Mexico (Valles-San Luis Potosi platform in red box (modified from Centeno-García et al., 2008). B) Schematic cross section showing the tectonic effects of the initial accretion of the Guerrero Composite Terrane over the calcareous platform rocks of eastern and southern Mexico (modified from Centeno-García et al., 2008). C) Schematic cross sections across the Valles–San Luis Potosi platform showing folding and thrusting of this platform during the late Cenomanian and the resulted irregular surface during the Turonian (modified from Smith, 1986).

This Cenomanian – pre-Santonian tectonic deformation may explain the following stratigraphic facts in east and northeastern Mexico:

1- The span of the hiatus over parts of Valles–San Luis Potosi (7 to 24 Ma) reported by Smith (1986).
2- The remarkable thickness variations of the Agua Nueva Formation observed along the eastern edge of the Sierra Madre Oriental from the Sierra del Abra to Cerro de la Silla.
3- The conspicuous thickness variations of the Agua Nueva Formation and Eagle Ford Groups reported in the Front Ranges (Sierra de Tamaulipas, Sierra de San Carlos, Sierra de Picachos, Sierra del Burro) by Muir (1936), Diaz (1952), Carrillo-Bravo (1961), and Bishop (1970).
4- The distinct thickness variations of the Agua Nueva Formation observed in the Tampico-Misantla Basin.
5- The evident thickness variations of the Agua Nueva Formation and Eagle Ford Group along the southwestern part of the Burgos Basin (Perez Cruz, 1993).
6- The absence of Late Cenomanian-Santonian strata on the western part of the Tuxpan platform (Sotomayor Castañeda, 1954; Enos, 1974).

Laramide Orogeny. Coniacian 89.8 Ma – Maastrichtian 66 Ma.

In the Interior Zone, the Coniacian-Santonian sediments rest unconformably upon the Turonian or Cenomanian rocks; and mark a change to carbonate deposition in areas where terrigenous clastics had previously prevailed. Thus, from the Rio Grande to Alabama a thick section of chalk and chalky marls (Austin Group) were deposited in the East Texas and Maverick Basins. This section is unconformity bound in many areas and shows a general thickening from the Sabine uplift to the west and southwest into the East Texas

Basin (Salvador, 1991a; Sohl et al., 1991). In northeast and east Mexico, the San Felipe Formation is equivalent in age and lithology to the Austin Chalk (Weise, 1987) (Figure 45).

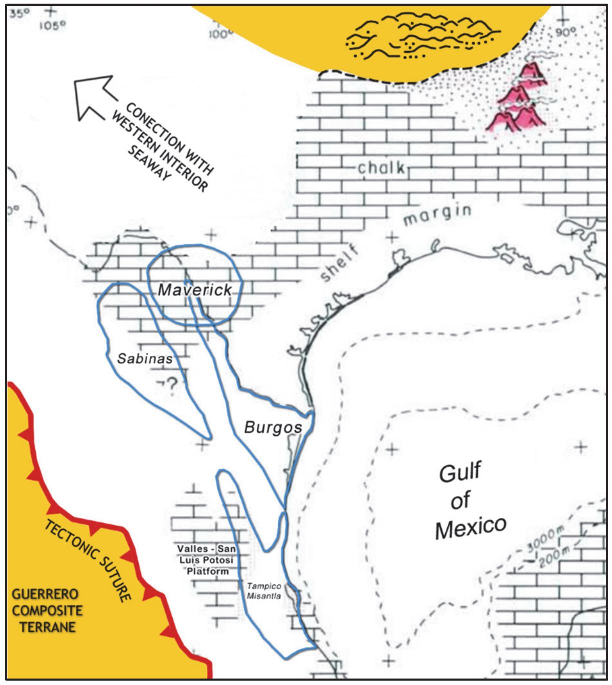


Figure 45: Paleogeography of the study area during the Coniacian-Santonian (modified from Salvador, 1991a).

During Campanian time, the effects of the Laramide tectonic began to be evident in the Interior and the Western Compressional Zones. Both zones began to subside and to be filled with siliciclastics derived from western and northwestern uplifted landmasses. Thus, in the Maverick and the Sabinas Basins, the prodelta deposits of the Anacacho and Upson Formations were deposited (Robeck, 1956; Weise, 1987; Tyler and Ambrose, 1986; Flores-Espinosa,1989). Eastward, the fine-grained rocks of the Mendez, Taylor Formation were deposited in deep water environments in central Texas, East Texas Basin, and in the present areas of the Burgos and Tampico-Misantla Basins, and the Valles-San Luis Potosi platform (Weidi, 1972; Sohl et al., 1991). During the mid-Campanian, an important peak in igneous activity took place in the Balcones volcanic center. The Cretaceous ended with a drop in the sea level which led to a considerable basinward retreat of the coast of the Gulf of Mexico (Salvador, 1991a) and the vanish of the communication between the Gulf of Mexico and the Western Interior Sea (Figure 46).

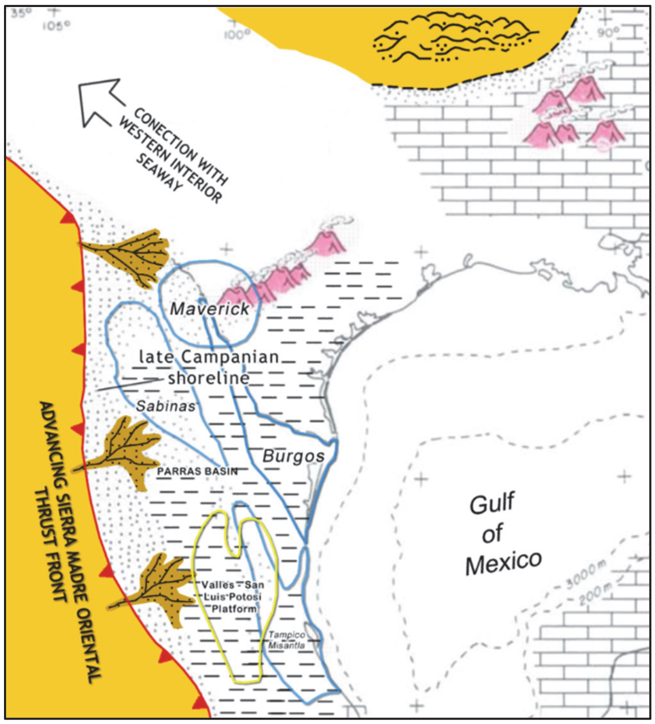


Figure 46: Paleogeography of the study area during the Campanian (modified from Salvador, 1991a).

In the Maastrichtian, the continued advance of the Sierra Madre Oriental thrust front led to the deposition of a thick sequence of sandstones and shales (San Miguel, Olmos, and Escondido Formations) in delta fronts that encompassed the areas of the Maverick, Sabinas Coal, and Parras Basins (Robeck, 1956; Weise, 1987; Tyler and Ambrose, 1986; Flores Espinosa, 1989). Basinward, the shales of the Mendez and Navarro

Formations still accumulated. By this time, volcanic activity decreased in the Balcones area (Sohl et al., 1991; Salvador, 1991a) (Figure 47).

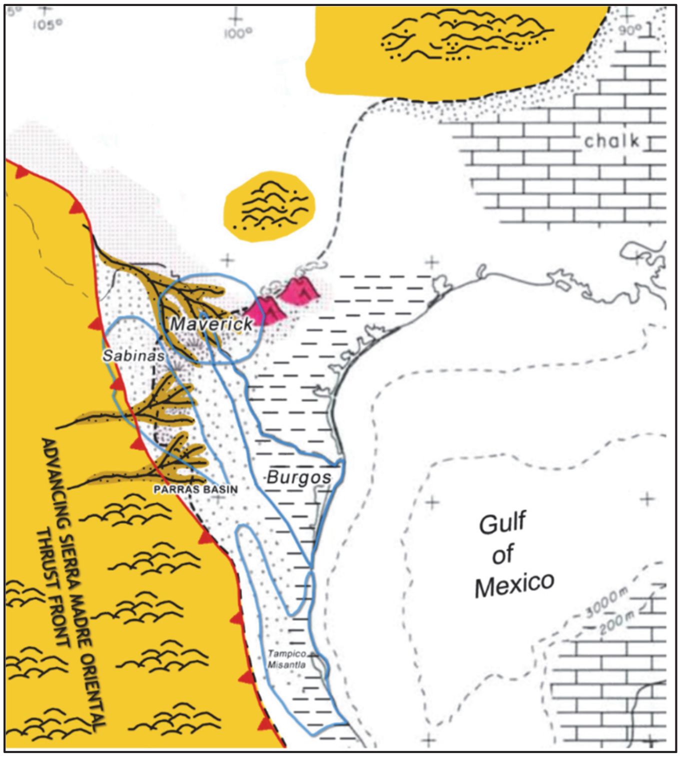


Figure 47: Paleogeography of the study area during the Maastrichtian (modified from Salvador, 1991a).

Late Stages of the Laramide Orogeny. Paleocene 66 Ma – Oligocene 30 Ma.

Gray et al. (2001) argue that during and after the late stages of the Laramide orogeny the Compressional Zone became an area where a foreland basin formed at the leading edge of the Sierra Madre Oriental foldbelt (Figure 48A). Thus, the Indidura and Agua Nueva Formations and the Eagle Ford Group began to be uplift at the foldbelt; whereas they actively subsided in the areas located in the foreland basin. According to Gray et al. (2001), the burial of this basin reached 7 km locally, and at least 5 km in the central portion; and temperatures were between 125° and 150° C about 50 Ma (Figure

48A). This basin covered the region now occupied by the Tampico-Misantla, Burgos, Sabinas and Maverick Basins (Figure 48A). Carrillo Bravo (1980) states that uplift and erosion of the foldbelt gave rise to the Chicontepec and Bejuco-La Laja canyons that cut the seafloor of the Tampico-Misantla Basin producing the erosion of the Agua Nueva Formation in some areas.

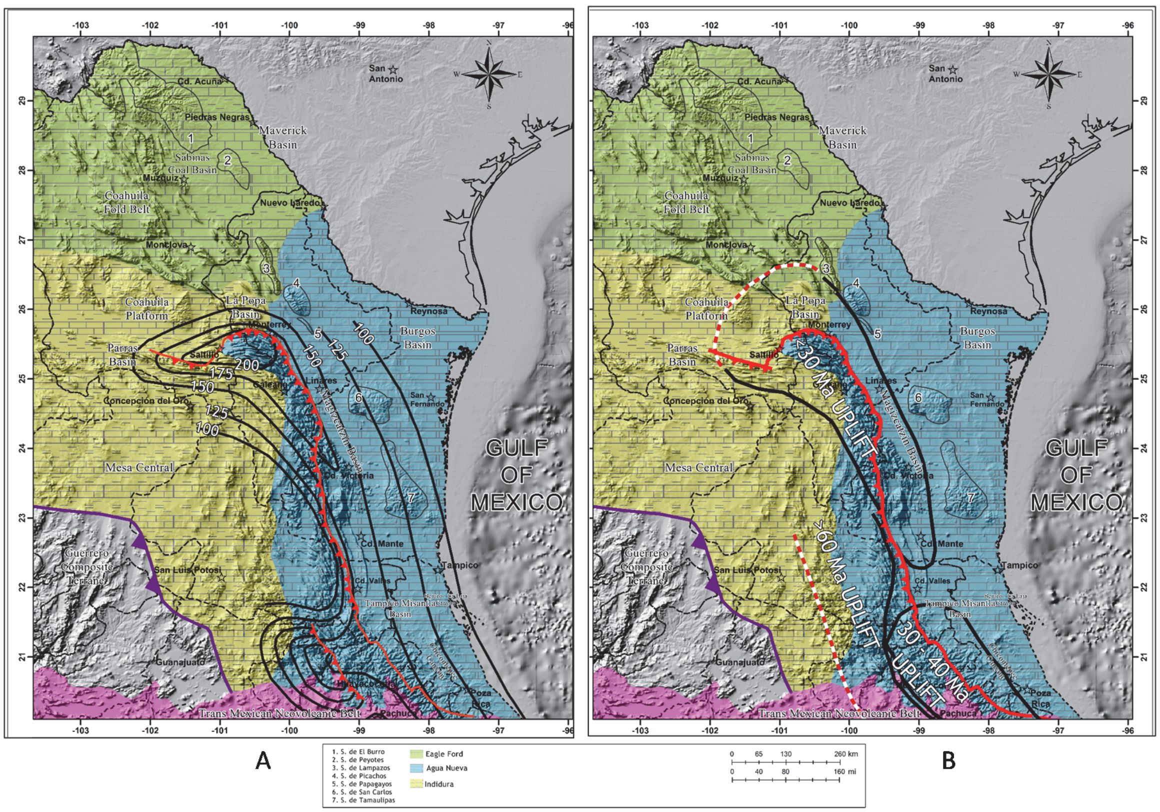


Figure 48: A) Contours of aqueous homogenization temperatures in the Tampico-Misantla Basin, showing two high temperature regions centered over the Monterrey Curvature and southwest of Ciudad Valles. B) Map showing three apatite fission-track ages provinces with different cooling age in the Sierra Madre Oriental (modified from Gray et al., 2001).

As the foldbelt migrated eastward, compressional stresses began to reach the Front Ranges and the Maverick Basin; and the Indidura and Agua Nueva Formations, and the

Eagle Ford Group began to be uplifted and eroded in the eastern front Sierra Madre Oriental and in the Front Ranges (Figure 48B). Simultaneously, the foreland basin reached its maximum burial in the Oligocene (Yurewicz et al., 1997) (Figure 21), and then began to be inverted and cooling (Gray et al., 2001). Hence, the main depocenters migrated into the Sabinas Coal Basin, the Maverick Basin, and the Burgos Basin (Figure 48B). As a consequence of these tectonic motions, the Agua Nueva Formation was buried below a Cenozoic section of 500 m to 2,300 m thick in the Tampico-Misantla Basin; whereas the Eagle Ford Group and the Agua Nueva Formation were buried below a thicker section in the Sabinas Coal, Maverick, and Burgos Basins (Galloway et al, 1991; Galloway, 2008).

In contrast with the Western Compressional Zone, in the Interior Zone the Laramide effects were subtle. In fact, Ewing (1987, 2012) suggests that the Frio River Line marks the dying out of Laramide folds and that the Chittim anticline of the Maverick Basin resulted from the Laramide reactivation of an ancient half-graben.

Key Findings

The structures of Tampico-Misantla, Sabinas Coal, Burgos, and Maverick Basins are the result of complex tectonic events; while the structures located east of the Frio River Line display mainly extensional features. The horst and graben topography produced during the rifting stage was of paramount importance in the Tampico-Misantla, Sabinas, and Maverick Basins because it controlled the stratigraphic pattern of the Eagle Ford Group and its equivalent formations in Mexico. However, it is evident that in east Mexico the paleorelief was modified and enhanced by the effects of shear motions that prevailed in eastern Mexico during the Late Jurassic. In addition, the compressional phase that took place in central Mexico in late Cenomanian began to reshape the paleobathymetry of the Mexican basins where the Eagle Group and equivalent formations were deposited. The uplifted western landmass that accompanied the late Cenomanian compressional event in central Mexico may have been an additional source for the detrital argillaceous sediments deposited in northeast and east Mexico. The compressional effects related to the Laramide orogeny began to change the geometry and structural styles of the basins drastically. This orogeny led to the uplift, folding, thrusting, and exhumation of a great part of the Late Albian-Turonian section in the eastern front of the Sierra Madre Oriental, in the Coahuila marginal foldbelt, and in the Front Ranges, while in Texas and east and northeast Mexico this section was buried in foreland basins under a section of Cenozoic sediments with contrasting thickness.

Chapter 4: Key Geotechnical Factors for the Success of the Eagle Ford Play and First Results of the Early Appraisal in Mexico

The Eagle Ford play in Texas produced its billionth barrel of crude and condensate in November 2014. More than 70% has been produced in the last two years. In 2014, it accounted for 16% of the total U.S. oil production (Wood Mackenzie, 2014). The success of the Eagle Ford play has spurred the possibility of replicating it in Mexico. However, the regional geological overview presented in the previous chapter demonstrates that a correlation between similar sediments of the same age is not straightforward.

Therefore, after understanding the primary regional geological control on the structural framework, thickness, depth, and heterogeneous lithology of the equivalent formations of the Eagle Ford in northeast and east Mexico, the next step is to look at the key geotechnical factors that make development of shale commercial, especially the Eagle Ford play, and the first results of the early appraisal of the Eagle Ford in Mexico. This information will permit a first approach to identify areas in northeast and east Mexico which will be discussed in Chapter 5.

CONCEPTUAL FRAMEWORK

Successful shale plays are characterized by the following controls on shale gas and oil prospectivity (e.g. Kuhn et al., 2001; Zagorski et al., 2012; Wang and Gale, 2009; Cander et al., 2013; Waldo, 2015):

- Total organic carbon (TOC)
- Thermal Maturity (Ro)
- Depth
- Thickness
- Pressure gradient

- Fluid viscosity
- Porosity
- Permeability
- Tectonic setting, natural fracturing, and subsidence history
- Mineralogy and Brittleness

Total organic carbon (TOC) is a measure of the concentration of organic material in a sedimentary rock and is represented by the weight percent of organic carbon (Jarvie, 1991). The minimum cut off for shales as source rocks is usually considered to be 0.5% TOC (Table 9). The quantity of organic matter that is incorporated into sedimentary rocks depends on variables such as sedimentation rate, organic productivity, depositional environment and the post-depositional, or diagenetic history of the basin (Dow, 1977). As the organic matter is buried under mild temperature and pressure conditions, it is transformed into kerogen through diagenesis (Tissot and Welte, 1978). As the kerogen is buried deeper, it is transformed because it is subjected to higher temperature and pressure. The stage of catagenesis corresponds to the main zone of oil generation and also to the beginning of the cracking zone, which produce wet gas; while the stage of metagenesis is entirely situated in the dry gas zone (Tissot and Welte, 1978).

Petroleum Potential	TOC (wt. %)
Poor	0.0-0.5
Fair	0.5-1.0
Good	1.0-2.0
Very good	2.0-4.0
Excellent	>4.0

Table 9: Total organic carbon wt. % describing the petroleum potential of source rocks (Peters and Cassa, 1994).

Kerogen type determines which type of hydrocarbons are being generated. Kerogen type I produces oil, waxy oil is produced by kerogen type II; and gas by kerogen type III, although often a mixture of one or the other kerogen types might be present. Vitrinite reflectance (Ro) is a diagnostic tool for assessing maturation in addition to pyrolysis as is shown in (Figure 49). Organic-rich sediments have a lower density, lower sonic velocity, higher porosity, higher resistivity, and higher gamma-ray values compared with sedimentary rocks of equal compaction and comparable mineralogy (Herron, 1991). TOC of prospective areas equal to or greater than 2% and Ro typical values ranging from 1% to 3% may lead to the presence of nanopores, contributing to additional porosity from pores in the organic matter (Loucks et al., 2012; Chopra et al., 2014).

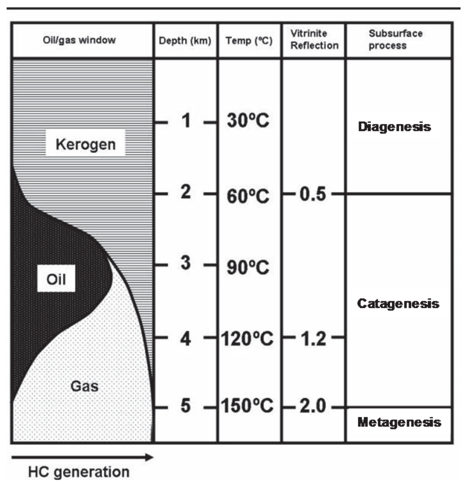


Figure 49: General scheme of hydrocarbon formation as a function of burial of the source rock (source Oil and Gas Geology, 2010) a) Ro < 0.7%, diagenesis stage, source rock immature; b) 0.5%-0.7%<Ro<1.3%, catagenesis, main zone of oil generation (oil window), c) 1.3%<Ro<2% catagenesis stage, zone of wet gas and condensate, d) Ro>2% metagenesis stage, methane remains as the only hydrocarbon (dry gas zone) (Tissot and Welte, 1978).

Jarvie et al. (2007) point out that organic richness, kerogen type, and thermal maturity impact the sorptive capacity of organic matter. Sorption capacity also affects expulsion efficiency. Another economic key point is stated by O'Connor et al. (2014) who indicate that low-pressure areas negatively impact productivity of a play, whereas, in overpressure areas the effective stress is low, compaction is inhibited, and porosity is preferentially preserved. Overpressure increases flow rate for a given permeability. Periods of continued subsidence favor overpressure, whereas uplift phases and unconformities lead to pressure dissipation. The gas generation creates additional overpressure (O'Connor et al., 2014). Loading burial can generate considerable overpressure, especially during the rapid subsidence of low-permeability sediments; and horizontal stress changes can rapidly generate and dissipate a large amount of overpressure in tectonically active areas. Hydrocarbon generation and cracking create overpressure (Jarvie et al. 2007). Reservoir pressure and viscosity are critical for understanding mobility of petroleum; viscosity is a function of gas and oil ratio, which is a function of maturity. As maturity increases, gas-oil ratio (GOR) increases and viscosity decreases, but this prediction can fail if burial and tectonic history are not well understood (Cander, 2013).

Brittleness of rock is a measurement of the ability of the rock to crack or fracture (fracability) and is a complex function of lithology, mineral composition, TOC, effective stress, reservoir temperature, diagenesis, thermal maturity, porosity, and type of fluid (Wang and Gale, 2009). The brittleness index (BI) increases with presence of quartz and dolomites and tend to decrease with the presence of clay and calcite, because they increase ductility (equation 1) (Jarvie et al., 2007; Wells, 2004 in Wang and Gale, 2009).

$$\text{Equation (1): } BI = \frac{Quartz+Dolomite+Calcite}{(Quartz+Dolomite+Calcite+Clay)}$$

Good shale producer reservoirs have good brittleness properties with high Young's modulus and low Poisson's ratio (Griesser et al., 2007 in Wang and Gale, 2009). The effect of depth on brittleness is compounded because an increase in depth generally increases pressure and temperature. The onset of chemical compaction and clay diagenesis reduces porosity and permeability and increase brittleness (Wang and Gale, 2009; O'Connor, 2014) (Figure 50).

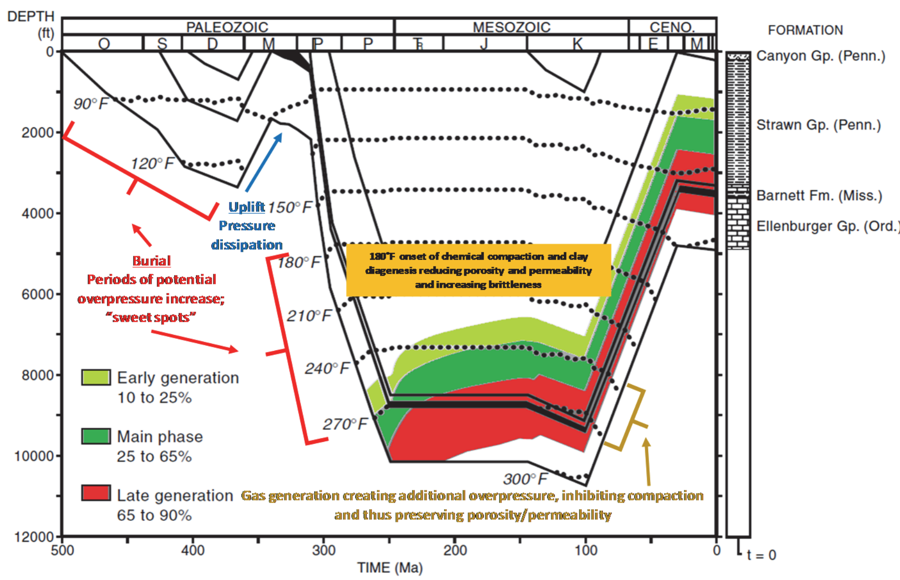


Figure 50: Example of burial history diagram and stratigraphic column in Fort Worth Basin showing the effects of burial and uplift over pore pressure (modified from O´Connor, 2014, after Jarvie et al., 2001 and Curtis, 2002).

Curtis (2002) demonstrated that fixed value criteria cannot adequately be applied to all shale gas systems. For this reason, Wang and Gale (2009) proposed that depth-dependent parameters are crucial for the screening of any shale-gas systems. These parameters are thermal maturation, thickness, gas content, absorption, and brittleness. Organic-rich shales with TOC greater than 1%, Ro greater than 0.4%, gas content greater than 40 scf/ton, and thickness greater than 10 m are potential candidates for shale-gas production (Russum, 2005 in Wang and Gale, 2009).

Key Geotechnical Factors for the Success of the Eagle Ford Play

The key geotechnical factors of the main sweet spots in the Eagle Ford play are summarized in Table 10.

Parameters	Eagle Ford Play	Maverick Basin	Hawkville Field	Black Hawk Field (Karnes Trough
Depth (m)	458-4,268	458-2,286	3,200- 3,810	2,740-3,200
Average Thickness (m)	15-122	50-107	37-100	37 - 82
Average Porosity φ (%)	3-10			
Pemeability (nd)	3- 405			
TOC (%)	2-12	1-14 (Lower EF)	2.75-6.82 (La Salle County)	N/D
Type of Kerogen	II and II/III			
Thermal Maturation (%Ro)	0.45 -1.4 Oil, codensate, and gas windows	.45-1.0	.75-1.32 (Upper EF) .55-1.3 (Lower EF) Transition wet gas to dry gas	Transition oil and condensate
Mineralogy	65-75% carbonates, 10 - 20% clays, 15-20% silica, 10-12% kerogen	30-90% carbonates (Lozier Canyon)	20% silica, 50% calcite, 20% clay, 10% kerogen	
Geological structure	Regional homocline dipping basinward	Anticline	Homocline dipping basinward	Graben
Pressure Gradient (psi)	5,500 -10,500	6,000 max.	N/D	10,500 max

Table 10: Regional and local key geotechnical parameters of the Eagle Ford play (data from Tuttle, 2010; Amoss et al., 2011; Martin et al., 2011; Arguijo et al., 2012; Donovan et al., 2012; Pope et al., 2012; Gong et al., 2013; EIA, 2014a; Pathak et al., 2014; Tian et al., 2014; Tinnin et al., 2014).

Geographically, the Eagle Ford play is 81 km wide and 644 km long and covers 23 counties of South-Central Texas. The top of the Eagle Ford Group ranges between 457 m and 4,268 m, and the pay thickness varies between 38 m and 91 m (Martin et al., 2011; EIA, 2014a) (Figure 51). In Maverick Basin, the reservoir thickness exceeds more than 100 m facilitating operators to drill and stay within the target formation with the lateral. In general, reservoir thickness is greatest along the Stuart City trend margin and in Maverick Basin (Amoss et al., 2011).

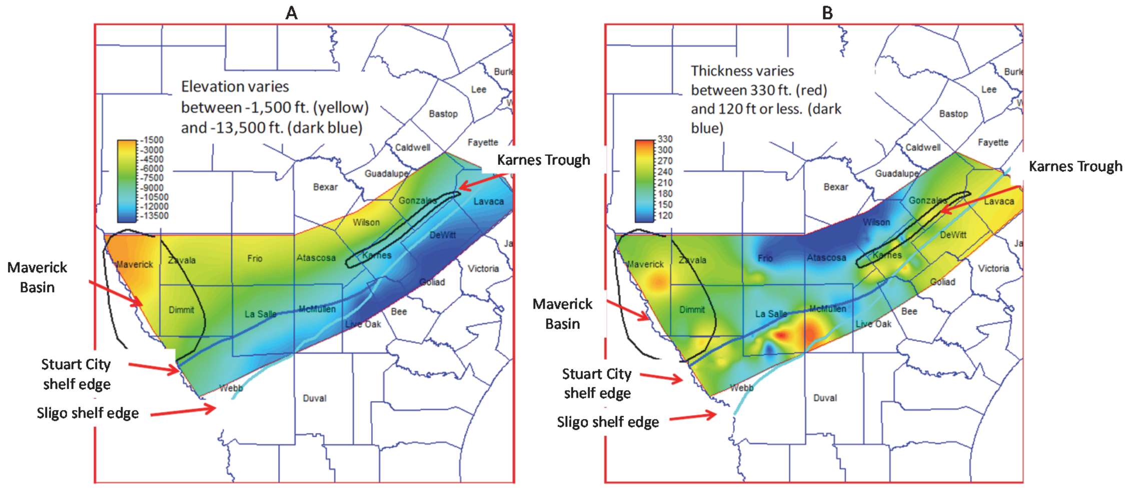


Figure 51: A) Top Eagle Ford "Shale" structure map with geologic features (modified from Martin et al. 2011). B) Eagle Ford "shale" thickness map with key geologic features (modified from Martin et al., 2011).

The Eagle Ford play has three maturation windows (oil, condensate, and natural gas) as it dips basinward (Ilk et al., 2012). Hence, the north-western portion of the play is more oil, the middle segment yields condensate and wet gas, and the southern-eastern portion is largely dry gas. The EIA (2014) shows that the three windows of the Eagle Ford play are between 1,220 m in the northwest and 4,268 m in the southeast (Figure 52). In the Eagle Ford play, reservoir depth has important economic consequences because it is crucial for reservoir pressure, hydrocarbon flow rate, and well cost (Amoss et al., 2011).

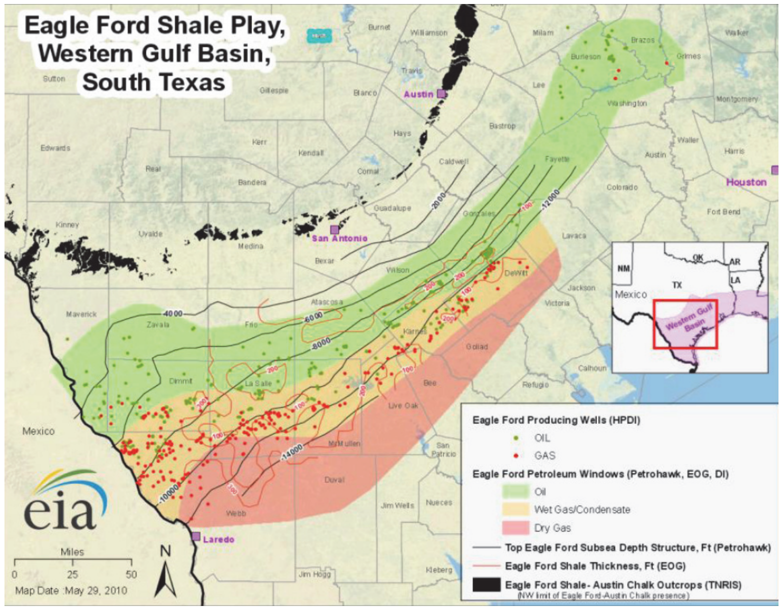
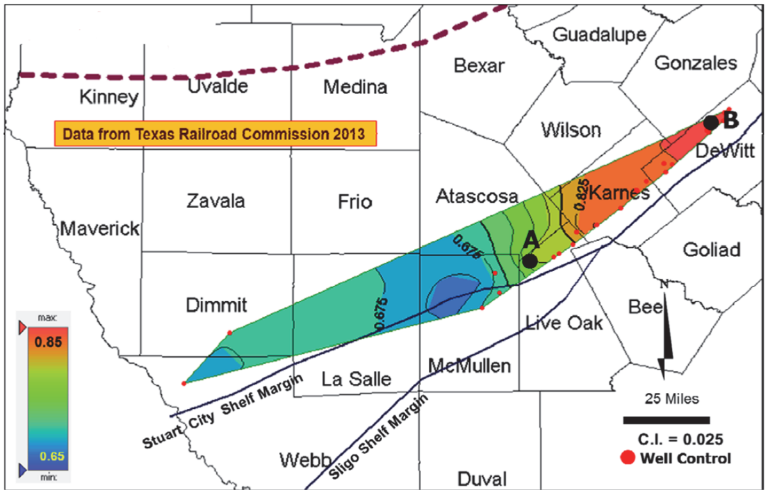


Figure 52: EIA, 2010 Eagle Ford play Map showing the three petroleum windows (EIA, 2014a).

Hydrocarbons from the Eagle Ford charged the Woodbine sands in the East Texas Basin, and in central and south Texas, the Austin Chalk. The Eagle Ford Group is part of the same hydrocarbon system, since hydrocarbons in both units were sourced from kerogen type II and II/III, that mature in deeper southern parts of the play (Martin et al., 2011; Pathak et al., 2014). According to the EIA (2014), TOC values range from 2% to 12%, Ro from 0.45% to 1.40%, API gravity from 28° to 62°, porosity from 8% to 12%, and pressure gradient from 0.5 to more than 0.8 psi/ft.

Tian et al. (2014) observed that API gravity increases from northwest to southeast from 43° to more than 60° API, and pressure gradient increases from 0.65 to 0.85 psi/ft along a swath parallel to the Stuart City Reef Margin (Figure 53). Regional overpressure has been generated through disequilibrium compaction as a result of rapid burial from Late Cretaceous to Paleogene as well as maturation of hydrocarbons. Gas content enables the oil molecules to flow through the rock with less resistance, leading to higher reservoir pressure and flow rates vs. the oil window to the north.

A



B

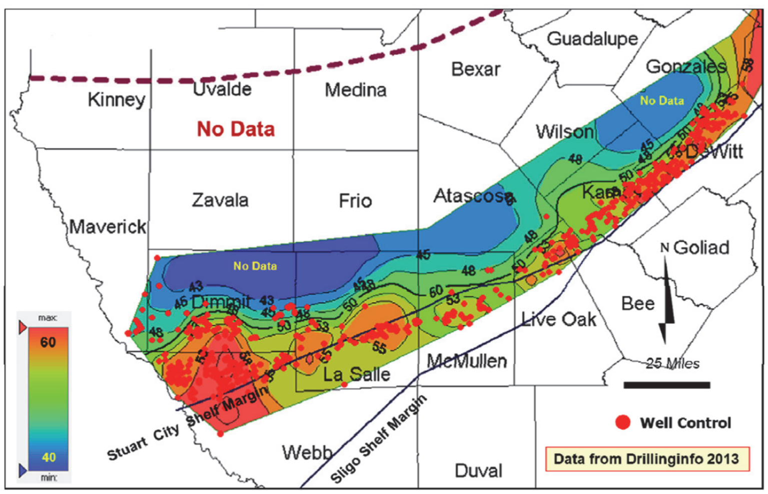


Figure 53: A) Pressure gradient and B) oil API gravity trends of the Eagle Ford play (Tian et al., 2014).

Mineralogy in the Eagle Ford Group consists typically of 65% to 75% carbonate, 10% to 20% clays, and 15% to 20% silica; hence, it is considered a calcareous marlstone when designing the completion and hydraulic fracture stimulations (Pope et al., 2012)

(Figure 54). The high carbonate content makes the Eagle Ford Group a brittle rock that makes the artificial fracturing process easier and more productive.

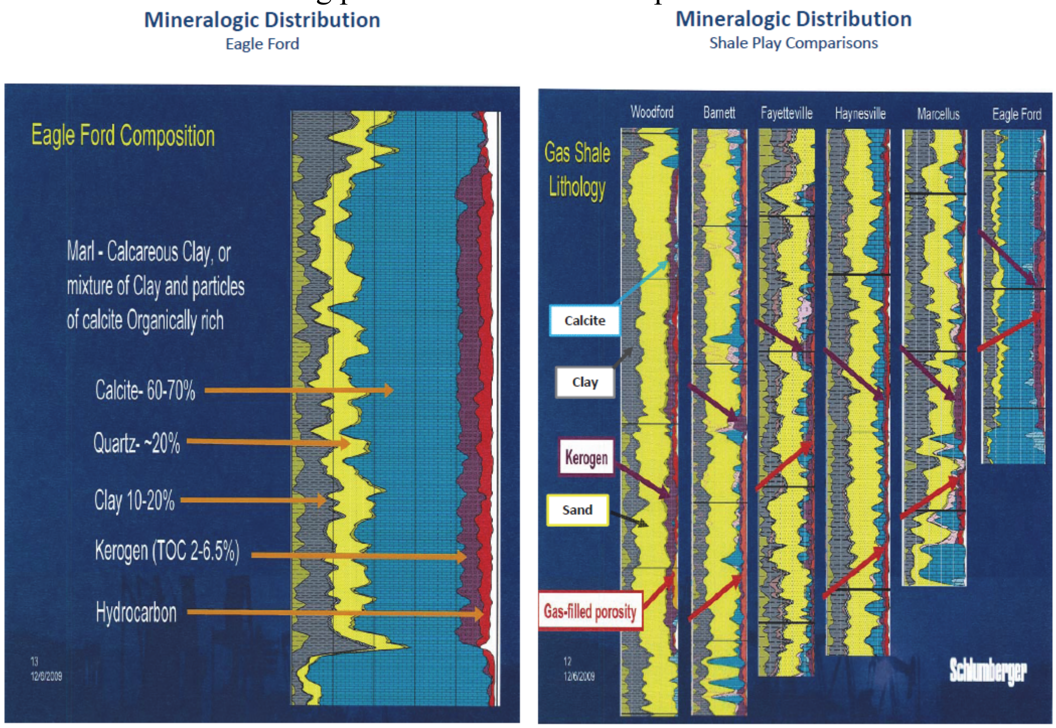


Figure 54: Eagle Ford play lithology vs. other shale plays (Rosetta Resources, 2010 in Amoss et al., 2011).

However, it is important to consider that in regional terms the clay volume increases towards the northeast where the Eagle Ford Group interfingers with the siliciclastics of the Woodbine Formation. In this context, one of the largest operators in Eagle Ford, Pioneer, states that the two key performance indicators in their acreage in DeWitt and Karnes counties are TOC and brittleness (Tinnin et al., 2014). These authors have observed that well performance in the central segment of the play area is a function of clay volume (less than 30%) and TOC (greater than 2.5%). These authors point out that the presence of the trace element molybdenum is a good indicator of oxygen-depleted waters (anoxic conditions), when its concentration is greater than 10 ppm. In addition, Tinnin et al. (2014)

reported that wells drilled in the clay-rich environment experienced significant trouble associated with drilling and completing, whereas completion effort was very successful in the wells drilled in the carbonate-rich section (Bodziak et al., 2014) (Figure 55).

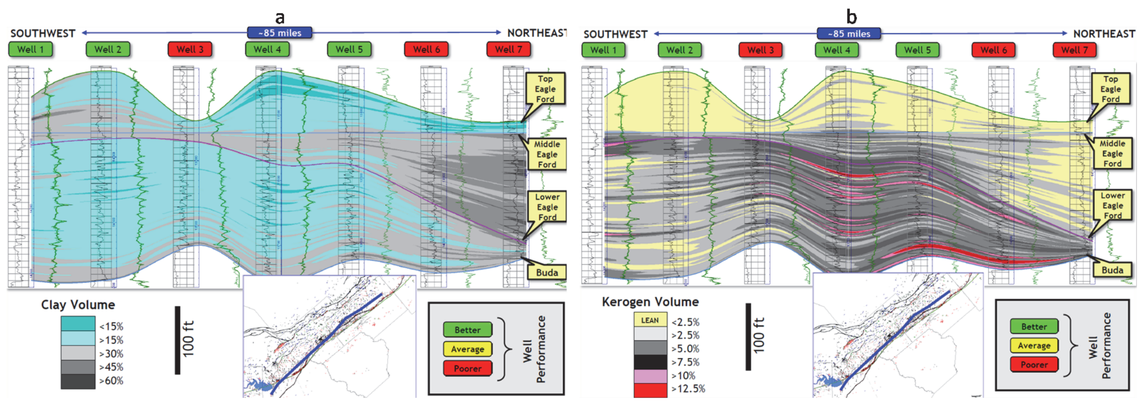


Figure 55: A) Facies Variability: VClay (Brittleness); and B) Facies Variability TOC (Kerogen) (Tinnin et al., 2014)

Porosity and permeability vary across the area of the play. Martin et al. (2011) considered that effective porosity ranges from 3 to 10% with a mean of 6%, while permeability ranges between 3 nd and 405 nd with an average value of 180 nd. The aforementioned values vary significantly because the heterogeneous lithology of the Eagle Ford Group.

Eagle Ford Play Sweet Spots

Hawkville and Black Hawk Areas

According to Amoss et al. (2011), the core geographic areas that are all highly economic within the Eagle Ford play extend in a narrow swath of acreage running from southwest to northeast in the condensate-volatile oil window in La Salle, McMullen, Live Oak, Karnes, DeWitt, and Gonzales counties. Even though, the wells in this area are not necessarily the highest EUR wells; the higher relative liquid content has been providing better economic return given higher prices for oil and liquids than natural gas, especially until late 2014 when the price of oil fell. The sweet spot located between the Stuart city and Sligo reef margins is also known as the Hawkville field while the sweet spot situated in the Karnes trough is known as the Black Hawk field.

The location of these two sweet spots demonstrates that the structural setting controlled bathymetry and facies, which in turn control production. Martin et al. (2011) considered two type logs that show this influence on lithology and other key geotechnical factors between these two sweet spots. In the log located in the Hawkville field (La Salle County) the Eagle Ford Group is 67 m thick and mostly consists of black shales through the transgressive and regressive intervals (lower and upper members of the Eagle Ford according to Donovan et al., 2012). In contrast, in the log located in the Black Hawk field (Karnes County) the Eagle Ford Group is 88 m thick and displays the transgressive organic-rich black shales and the regressive intervals. The regressive interval consists of fractured limestones, calcareous shales, and bentonites. Martin et al. (2011) interpreted the dominance of black shales in the upper regressive interval as the result of deposition further downdip in a deeper marine environment. In these two wells, the mineral content varies little (20% quartz, 50% calcite, 20% clay, and 10% kerogen). Effective porosity ranges from 3% to 10% with a mean of 6%. Permeability ranges from 3 to 405 nd, with an average of 180 nd.

The Hawkville area is at the transition point between wet gas and dry gas while in the Black Hawk area the hydrocarbons are primarily oil and condensate. Kerogen types II and II/III are found in the Hawkville area and primarily type II in the Black Hawk field area (Tuttle, 2010; Edman and Pitman, 2010 in Martin et al., 2011). The best oil production occurs in the Black Hawk area because oil was trapped in natural fractured Eagle Ford shale close to the bounding faults of the Karnes Trough. Oil from continuous generation in the Karnes Trough migrated northward along bedding planes until the hydrocarbon became trapped in the highly fractured Austin Chalk in the Pearsall and Gonzales fields (Figure 56).

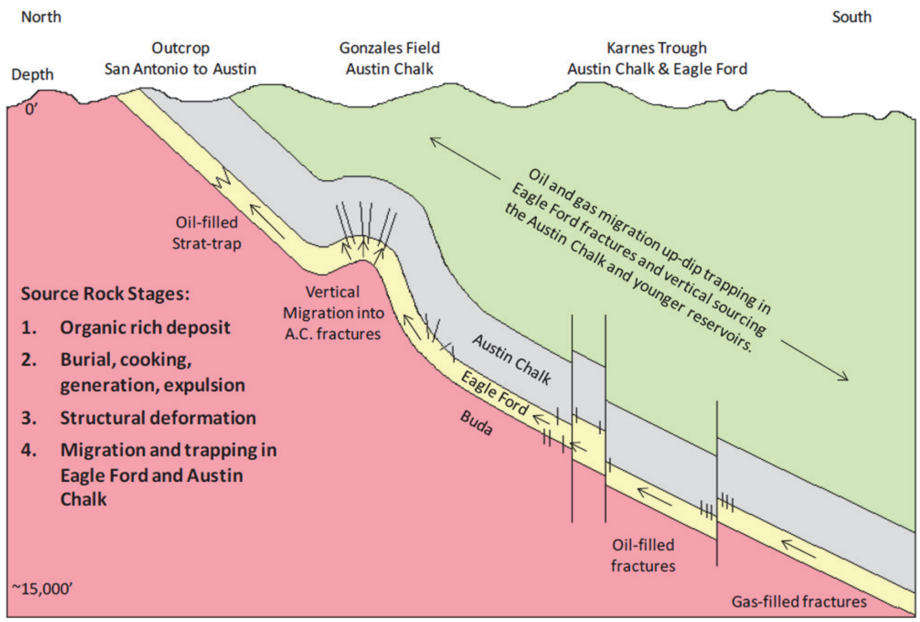


Figure 56: Cartoon illustrating updip migration of the Eagle Ford hydrocarbon through bedding planes and natural fractures. In the Karnes Trough, sealing faults played an important role in trapping the hydrocarbons (Martin et al., 2011).

MAVERICK BASIN. A KEY AREA FOR THE ASSESSMENT OF SHALE RESOURCES IN MEXICO

The Maverick Basin is a key area to assess the potential of the Eagle Ford play in the Mexican side because it straddles Texas and northeast Mexico. This basin lies in the oil and wet gas generation windows and updip of the Hawkville basin. According to Gong et al. (2013), on the basis of geology, fluid type, and production indicators, the Maverik Basin is located in the western segments of regions 1 and 2 (Maverick, Zavala, Demmit, and Northwest Webb Counties) (Figure 57).

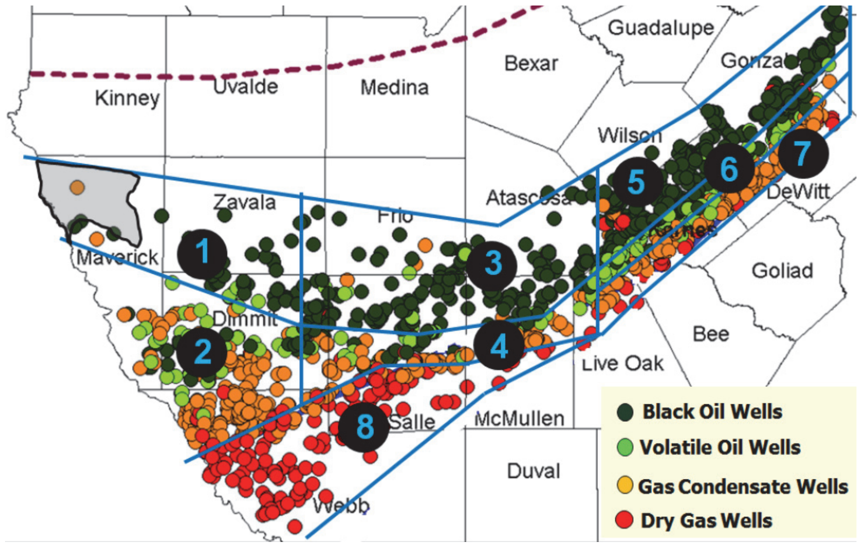


Figure 57: Fluid type changes from black oil to dry gas from north to south (modified from Tian et al., 2012 in Gong et al., 2013)

The top of the Eagle Ford in the Maverick Basin is at a depth that ranges from 458 to 2,286 m, and the thickness ranges from 50 to 107 m (Arguijo et al., 2012; Gong et al., 2013). Regionally, the northwestern part of the basin is the shallowest region of the Eagle Ford play, while one of the greater thickness of this formation lies just behind the Hawkville area (Martin et al., 2011). In this basin, the lower Eagle Ford shale is organic-rich (high gamma ray and high resistivity) and is present throughout the basin (Tian et al., 2012); however, productivity in the northwestern part of the basin (Maverick County) may suffer from shallow depth and resulting lower reservoir pressure (Tian et al., 2014). Even though, reservoir pressure increases into 6,000 psi in southern Dimmit County; this pressure is substantially lower than in the Karnes Trough where it reaches 10,000 psi (Tian et al., 2014).

Gong et al. (2013) consider that the northwestern part of the Maverick Basin is likely to be nonproductive because of the low initial reservoir pressure associated with shallow depth. In Zavala County and in the central part of the Maverick Basin, the Eagle

Ford produces black oil, which changes to volatile oil and gas condensate towards the Dimmit and the northwestern part of the Webb County. When the second month oil production is taken as a production indicator, wells in the Maverick Basin have lower performance in comparison to the central and northeastern part of the Eagle Ford play (Drillinginfo, 2013 in Gong et al., 2013) (Figure 58). A similar trend was observed by Amoss et al. (2011) but he mentions that the data may be somewhat skewed by a number of wells drilled and do not tell the whole story.

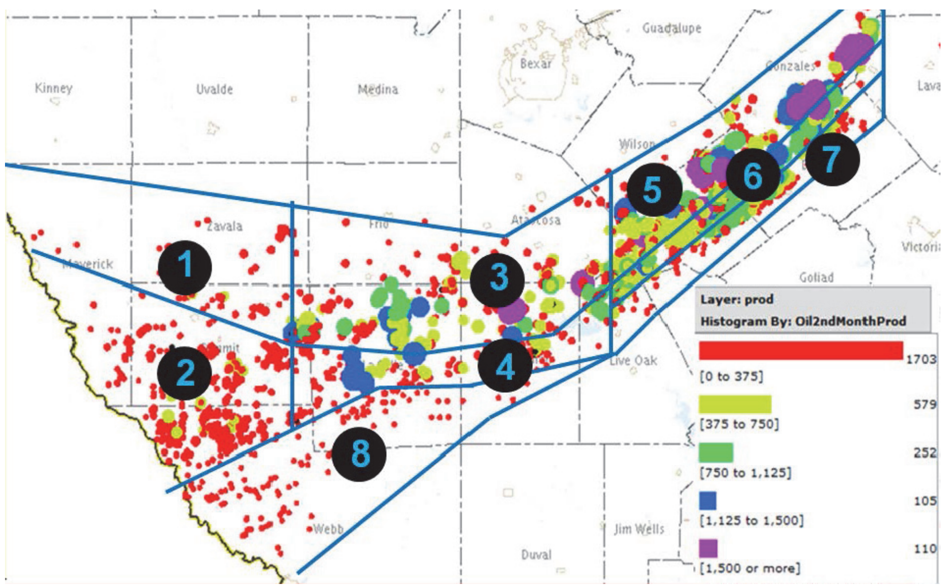


Figure 58: Second-month oil production used as a production indicator (Gong et al., 2013).

First Results of the Early Appraisal of the Eagle Ford in Mexico

Román Ramos et al. (2011) on the basis of information of forty-one wells, published a structural map at the top of the Eagle Ford Group/Agua Nueva Formation, as well as organic richness and thermal maturity maps of this unit, in which they displayed wet and dry zones in the Maverick, Sabinas Coal, and Burgos Basins (Figure 59). The EIA (2013) estimates on the Burgos and "Sabinas" Basins only refer to the gas and oil potential of these basins, but it does not provide the geochemical grounds of this assertion and does not forecast the expected hydrocarbon of the Agua Nueva Formation in the Tampico-Misantla Basin (Table 11). The USGS (Schenk et al., 2014) refers to the oil, gas, and natural gas liquids potential of the Agua Nueva Formation in the Tampico-Misantla, Burgos, and Sabinas Basins (Table 11). Therefore, large uncertainty exists about the expected hydrocarbons, and more research is needed to improve the understanding of Eagle Ford in Mexico, which could have important economic impacts.

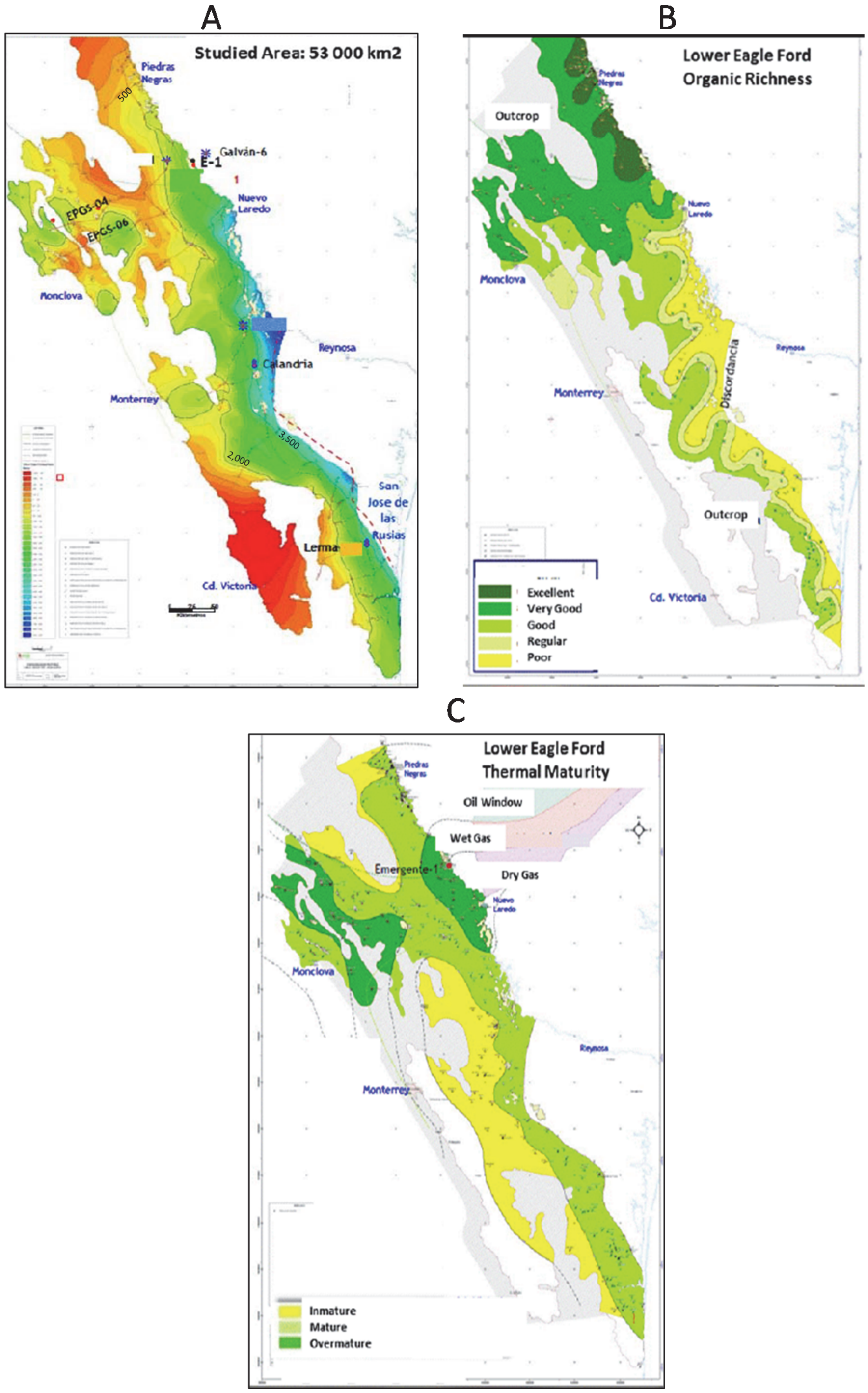


Figure 59: A) Top of the Lower Eagle Ford Group/Agua Nueva Formation. B) Organic richness. C) thermal maturity of the Lower Eagle Ford/Agua Nueva in northeastern Mexico (Román Ramos et al., 2011).

<table>
<tr><th></th><th>CNH</th><th>EIA</th><th>USGS</th><th>CNH</th><th>EIA</th><th>USGS</th><th>USGS</th></tr>
<tr><th>Province</th><th>Oil (Bbbl)</th><th>Technically Recoverable oil and condensate (Bbbl)</th><th>Unconventional oil resources mean (Bbbl)</th><th>Dry and Wet Gas (Tcf)</th><th>Technically Recoverable natural gas (Tcf)</th><th>Unconventional gas resources mean (Tcf)</th><th>Natural Gas Liquids (Bbbl)</th></tr>
<tr><td>Tampico-Misantla</td><td>13.4</td><td>0.0</td><td>0.43</td><td>42.0</td><td>0.0</td><td>0.8</td><td>0.2</td></tr>
<tr><td>Burgos</td><td>0.0</td><td>6.3</td><td>0.14</td><td rowspan="2">55.0</td><td>343.0</td><td>9.4</td><td>0.4</td></tr>
<tr><td>Sabinas</td><td>0.0</td><td>0.0</td><td>0.0</td><td>100.0</td><td>3.7</td><td>0.1</td></tr>
<tr><td>TOTAL</td><td>13.4</td><td>6.3</td><td>0.56</td><td>97.0</td><td>443.0</td><td>13.9</td><td>0.7</td></tr>
</table>

Table 11: Assessment of shale gas and shale oil resources of the “Mexican Eagle Ford Group” and Agua Nueva Formation (EIA, 2013; CNH, 2015; Schenk et al., 2014).

The most recent CNH (2015) summary about shale gas and oil in Mexico indicates that between 2011 and 2013 PEMEX completed eight wells to test the potential of the Eagle Ford play (Table 12). According to Escalera Alcocer (2012a; 2013b; 2013c), these wells are in the area he named “Sabinas-Burro-Picachos-Burgos,” and were drilled with the aim of proving the extension towards the Mexican side of the oil, wet gas, and dry gas windows of the Eagle Ford Group (Table 12). More precisely, the wells Emergente-1, Habano-1, Nomada-1, Montañes-1, Chucla-1, and Gamma-1 are located in the Mexican Maverick Basin, the Percutor-1 well in the Sabinas Coal Basin, and the Durian-1 well in the northwestern-most end of the Burgos Basin (Figure 5). Dominguez Vargas (2014) and CNH report (2015) disclosed the “initial production (Qi)” of seven of these wells and their results; while Martínez Sierra (2014) announced the result of the Gamma-1 well. Dominguez Vargas and the CNH report (2015) declare these wells as “commercial” or “non-commercial” without saying the technical and financial criteria to establish this status (Table 12).

Out of the six wells completed in the Maverick Basin, three were declared “commercial producer” with Qi ranging between 1.9 and 2.8 MMcfd (Dominguez Vargas, 2014; CNH, 2015) (Table 12). The Percutor-1 and the Durian-1 wells completed in the Sabinas Coal Basin and the Burgos Basin, respectively, were announced as “commercial producers of dry gas” with a Qi of 2.2 and 1.9 MMcfd (Dominguez Vargas, 2014; CNH, 2015).

#	Well	Basin	State	Completion	Initial Production (MMcfd)	Result
1	Emergente-1	Maverick	Coahuila	17-Feb-11	2.8	Commercial producer of dry gas
2	Habano-1	Maverick	Coahuila	15-Apr-12	2.8	Commercial producer of gas and condensate
3	Montañes-1	Maverick	Coahuila	30-Apr-12	0.1	Non-commercial producer of gas and condensate
4	Nomada-1	Maverick	Coahuila	30-Jun-12	NA	Non-commercial
5	Chucla-1	Maverick	Coahuila	30-Mar-13	1.9	Commercial producer of gas and condensate
6	Gamma-1	Maverick	Coahuila	22-Dec-13	0.3	Non-commercial producer of gas and condensate
7	Percutor-1	Sabinas Coal Basin	Coahuila	30-Mar-12	2.2	Commercial producer of dry gas
8	Durian-1	Burgos Basin	Nuevo León	5-Jul-13	1.9	Commercial producer of dry gas

Table 12: Eagle Ford exploratory wells in Mexico and their results (data from Dominguez Vargas, 2014; Martínez Sierra, 2014; CNH, 2015).

No detailed information has been published about the capital and operational expenditures of these exploratory wells. However, given that these wells were the first shale exploratory wells in Mexico, it is likely that the costs were above the average of those in Texas. Furthermore, the reports do not specify the meaning of “initial production Qi” (i.e. first month average production, first six months, first year). Therefore, the term “commercial” should be taken with caution.

According to the Lower Eagle Ford maps by Román Ramos et al. (2011), the six wells completed in the Maverick Basin are in a region where the total organic carbon (TOC) ranges from “good to very good” (Figure 59). Although, these authors do not state the TOC values of their classification; they may correspond to TOC values that range between from 1% to 4 % by considering the geochemical parameters of Peters and Cassa (1994) (Table 9).

The “non-commercial” wells, Nomada-1, Montañes-1, and Gamma-1, were drilled at depths shallower than 1,800 m in the northwestern part of the Maverick Basin, extension of the region where Gong et al. (2013) state the lack of enough depth to maintain an optimal pore pressure. On the other hand, the "commercial" wells, Emergente-1, Habano-1, and Chucla-1, were drilled at depths greater than 1,800 m. Therefore, it seems that the economic threshold in the Maverick Basin depends on the depth that reached the organic section of the Eagle Ford Group and other depth-dependent factors such as pore pressure and viscosity. These crucial factors were geologically controlled by the effects of the Laramide orogeny. Data published by Parra et al. (2013) seem to support this observation, since the pressure was greater in the Habano-1 well (4,000 psi) than in the Montañes-1 well (2,800 psi). However, with respect to the Montañes-1 well, these authors state that "it is suspected that the main reason for the poor production behavior is that it was not landed in the sweet spot rather in a poor quality rock." Furthermore, they remark that the Habano-1 well was drilled "inside the expected condensate window."

The Percutor-1 well completed in the central part of the Sabinas Coal Basin is located where the top of the Eagle Ford Group is between 1,500 and 1,750 m, the TOC values are "very good" and Ro values indicate "mature to overmature conditions" (Román Ramos et al., 2011) (Figure 59).

The Durian-1 well, completed in the northwestern end of the Burgos Basin, is located where the top of the Eagle Ford-Agua Nueva Formation is at a depth of ~3,250 m. The depth-contour map of Román Ramos et al. (2011) suggests that the basin ends towards the southwest, where the Sierras Lampazos and Picachos are present (Figure 59). Román Ramos et al. (2011) indicate that this area is the transition between "immature and mature conditions", and TOC values vary from "fair to very good". However, Serrano Bello et al. (1996) report a TOC of 1.15%, a Ro of 0.65%-1.0% and a kerogen type II and III for the source rocks of the Agua Nueva Formation in the Burgos Basin.

KEY FINDINGS

In Texas, the Eagle Ford play has three maturation windows (oil window, condensate window, and gas window) as it dips southeast. The three windows of the Eagle Ford play are between 1,220 m and 4,268 m. Reservoir depth has important economic consequences because it is crucial for reservoir pressure and hydrocarbon flow rate and well cost. The Eagle Ford Group is considered a calcareous marlstone when designing the completion and hydraulic fracture stimulation. Wells drilled in the clay-rich environment experienced significant trouble associated with drilling and completion, whereas completion effort is usually successful in wells drilled in the carbonate-rich section because of its better brittleness index.

The structural and paleogeographic setting controlled the location of the Hawkville and Black Hawk sweet spots. Thus, paleobathymetry and facies in turn control production. Productivity in the northwestern part of the Maverick Basin may suffer from shallow depth and resulting lower reservoir pressure.

In the early phase of Mexican shale gas and oil appraisal, eight wells were drilled: six in the Mexican part of the Maverick Basin, one in the Sabinas Coal Basin, and one in the northwestern end of the Burgos Basin. The shale potential Tampico-Misantla Basin has not yet been proved.

Three wells have proved the extension of the dry and wet gas windows in the Mexican Maverick Basin. The failure of the rest of the wells in this region seems to suggest that the economic threshold in the Mexican Maverick Basin depends on the depth the organic section of the Eagle Ford Group and other depth-dependent factors such as pore pressure and viscosity. In the Sabinas Coal Basin and in the Burgos Basin the presence of dry gas in the Eagle Ford Group has been proved by two wells.

In Mexico, publicly available information about geochemistry parameters is scarce, and no data have been published regarding the financial and technical criteria to consider the commercial viability of the wells. Hence, large uncertainty exists about the expected hydrocarbons and the potential future development of the Eagle Ford play. More work and research are needed to clarify this information as well as to define the sweet spots in the basins of northeast and east Mexico.

Chapter 5: Economic Shale Resources in Mexico

Is it possible to replicate the economic success of the Eagle Ford in Mexico? The best approach to answer this question is through the key findings discussed in Chapters 3 and 4 and through a summary geological map (Figure 61).

In Texas, east from the Frio River line, the main geological conditions that favored shale success in the Eagle Ford were associated with gentle tectonics that produced: 1) optimal lithology and structural conditions for hydraulic fracturing; 2) a burial history that allow the source rock intervals to move through the oil, wet gas, and dry gas windows; 3) adequate accommodation (space available for sedimentation to provide adequate thickness), brittleness (mineralogy and natural fractures), and the development of a relative regionally undisturbed homocline dipping to the southeast, with local depocenters such as the Karnes Trough.

West of the Frio River Line, in south Texas (Maverick Basin) northeast and east Mexico, tectonics was much more complex. Hence, lithology was more heterogeneous as demonstrated by the fact that three formal lithostratigraphic names have been used to describe the late Cenomanian-Turonian section. Complex tectonics may have negatively affected depth-dependent geotechnical factors such as Ro, oil and gas content, pore pressure, temperature, and viscosity. It is evident that in northeast and east Mexico, tectonics did not allow the development of regional structures favorable to produce well defined and predictable hydrocarbon zones, as is the case for the Eagle Ford play in Texas. The only exception is the Burgos basin, which consists of a well-defined monocline dipping toward the Gulf coast. Hence, the primary focus areas are those regions that received less input of argillaceous material during the late Cenomanian-Turonian, and remained buried at adequate depths for a good balance between maturation of organic matter, and preservation of pore pressure.

The focus areas (Figure 61) display the overlay of structural maps and distribution of the Eagle Ford, Agua Nueva, and Indidura Formations. This analysis is completed with the estimated depth of the target observed in the López Ramos (1972) and Wilson (1975), Perez Cruz (1993) and Barrios Rivera (2003) cross sections, the depth map provided by Román Ramos et al. (2011), the lithology reported in the literature, and PEMEX first results (Figures 5, 19, 21, 27, 29, 30, 31, and 59) (Tables 6 and 7). As stated in previous chapters, few geochemical data are available for this analysis. The assessment is not quantitative and the assessment units are the basins as they were delineated above.

In approximately two-thirds of the study area, the Eagle Ford Group and its equivalent were exhumed or eroded by the incision activity of submarine canyons (Figure 61). Therefore, these are non-prospective areas. In northeast Mexico, the Maverick Basin, the Sabinas Coal Basin, and the Burgos Basin remained buried. However, it is important to consider that the northwestern portion of the Mexican part of the Maverick Basin, the top of Eagle Ford Group is at similar depth as its Texas counterpart; hence, it is likely to be non-productive because of low initial reservoir pressure associated with shallow depth. The northeastern part of the Sabinas Coal Basin contains several depocenters where the Eagle Ford Group is at depths of the order of 2,000 m with a thickness ranging between 175 m and 300 m (Robeck, 1956; Eguiluz de Antuñano, 2011b) (Figures 19, 27, 60, and 61). In the Burgos Basin, the NW-SE cross section published by Barrios Rivera (2003), and the structural contour maps of Román Ramos et al. (2011) indicate a swath of 2,000 m to 4,000 m depth parallel to the Perez Cruz (1993) cross section (Figures 30 and 61). This cross section clearly shows that the Agua Nueva Formation is thinner and shallower around the northeastern flank of the Sierra de San Carlos. Along this swath, monocline folding may have produced faulting and fracturing in the Agua Nueva Formation. Therefore, the area between Nuevo Laredo and the Sierra de San Carlos seems to have better conditions to contain a sweet spot. This area is ~300 km long and ~100 km width. Another area of the Burgos Basin with good possibilities to contain a sweet spot for dry gas is the region located between the Sligo Trend and the southern limit of the Mexican part of the Maverick Basin. This area is ~100 km long and ~120 km wide.

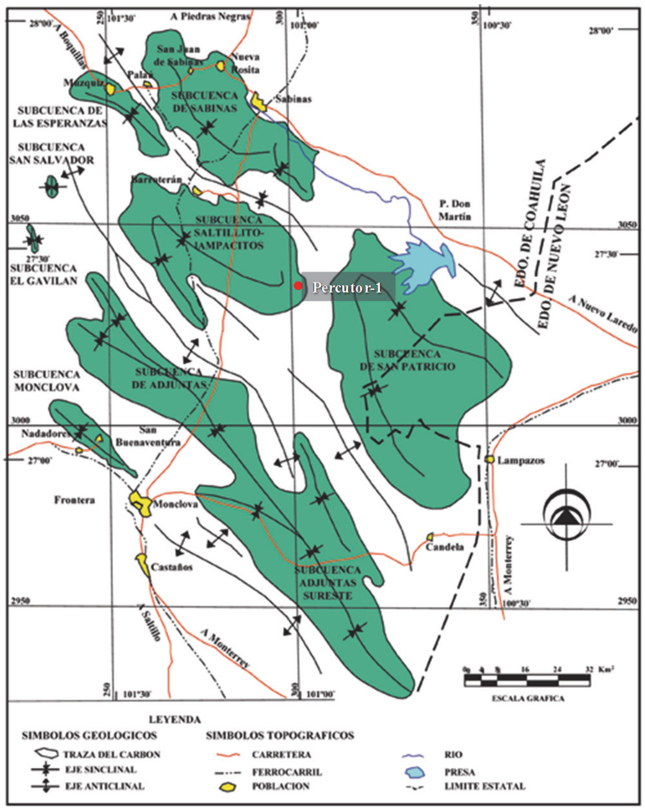


Figure 60: Main depocenters in the Sabinas Coal Basin (Rivera-Martínez and Alcocer-Valdés, 2003 in Corona-Esquivel et al., 2006).

The Tampico-Misantla Basin has a complex tectonic history in which periods of differential subsidence and regional uplift took place. The subsiding periods were favorable for the deposition and preservation of organic matter, as well as the generation and migration of hydrocarbons. However, the uplift periods associated with compressional stresses modify these conditions arresting the hydrocarbon generation and migration and probably dissipating the pore pressure. This situation is clearly shown by Yurewicz et al. (1997) who believe that in late Eocene and Oligocene, uplift of the western side of the Tuxpan platform arrested hydrocarbon generation to the west (Figure 21). Therefore, the prospective areas may be those regions were the effects of the tectonic uplift were subtle and where the Agua Nueva Formation was not eroded by the incision activity of the submarine canyons (Chicontepec and Bejuco-La Laja). According to López Ramos (1972) and Wilson (1975) cross sections (Figure 29A and 29B), these areas make up a northwest-southeast swath of ~300 km long and between ~50-130 km width located in the southern part of the Tampico-Misantla Basin. In this area, the Agua Nueva Formation is at depths ranging from 1,500-1,750 m in the northwest and 1,800-2,300 m in the southeast. The thickness of the Agua Nueva Formation in this area ranges from 100-200 m in the northwest and from 40-200 m in the southeast.

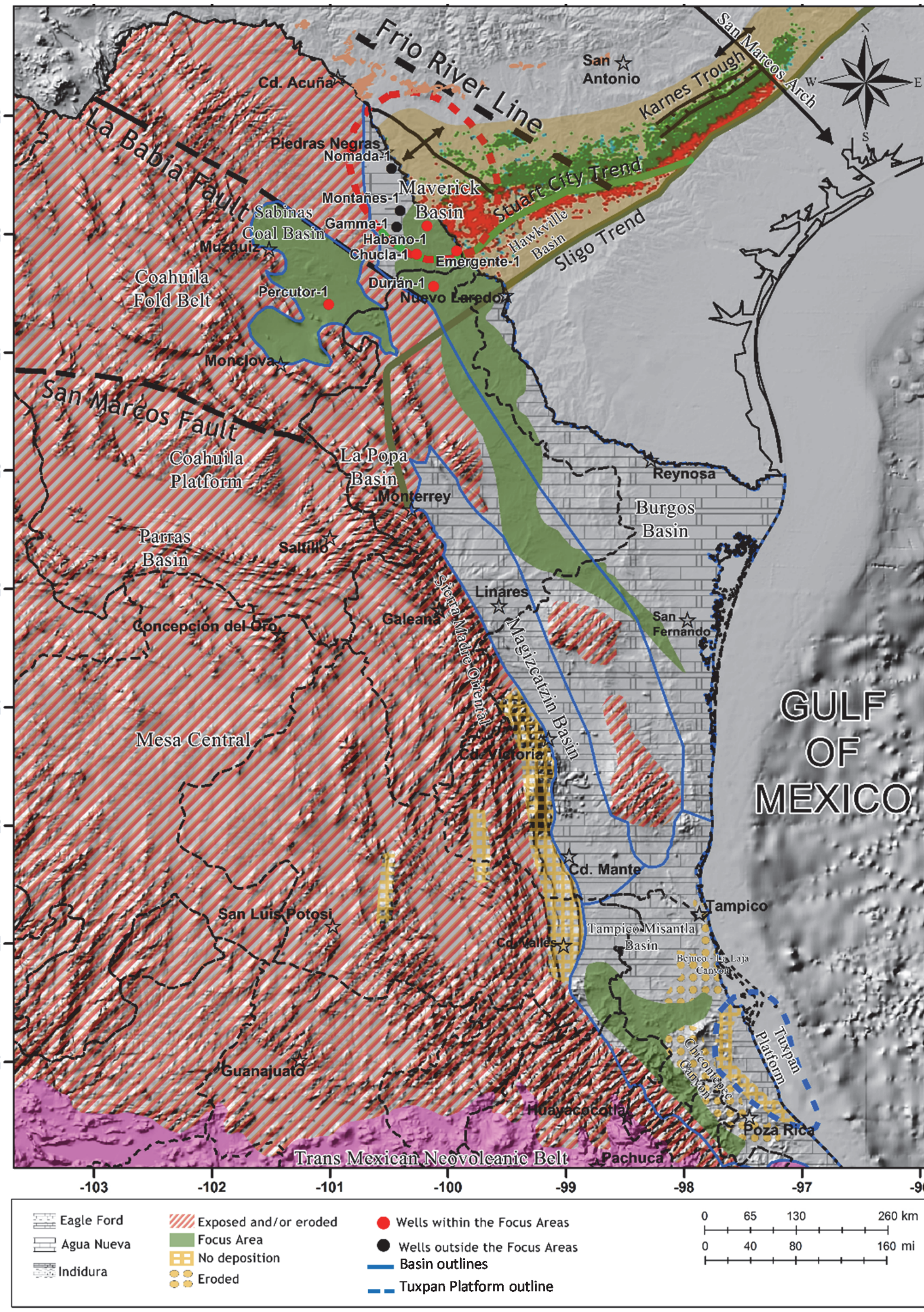


Figure 61: Map showing a sketch of three "Mexican Eagle Ford/Agua Nueva Focus Areas" (green), and areas where the equivalents formations of the Eagle Ford were exposed and/or eroded or not deposited (map elaborated on the basis of the information discussed in the text).

Chapter 6: Non-geologic Factors Necessary to Develop a Shale Industry in Mexico

In northeast and east Mexico there are focus areas with favorable geological conditions for the presence of shale gas and oil sweet spots. Hence, the concomitant question is how a shale industry might be developed in Mexico around these focus areas by taking into account the geographic features and other important non-geologic factors that made the success of this industry possible in the U.S. In order to answer this question, firstly, I present a brief geographic context of the focus areas, and discuss water resources, some population facts, socio-economic conditions, and road and pipeline infrastructure. Then, I explain the crucial roles that will play in Mexico's shale industry the legal and regulatory framework and the land and mineral ownership. And finally I make some considerations for development of a successful shale industry in Mexico.

GEOGRAPHIC CONTEXT

Mexico is a federal republic with three levels of government: federal, state (31 states plus the Federal District), and municipalities (2,457). Each State elects its governor and has its own constitution, and municipal authorities are chosen at the local level. According to the Mexican Constitution (Article 115), the basic unit of the Mexican government is the municipality ("Municipio Libre"). Municipal governments are responsible for a variety of public services, including water and sewage, street lighting, cleaning and maintenance, public safety and traffic. Mexico's recent energy sector reform should be seen within the context of this federal structure. Goodrich Riquelme y Asociados (2014) states that the institutional design of the 2013 Energy Reform "rests on a trinity" driven by federal entities: the CNH, the SHCP (Department of Treasury), and the SENER. Furthermore, the same report indicates that the SEDATU (Department of Agrarian, Territorial, and Urban Development) should be in charge of issuing "guidelines and contract models for land use and superficial occupancy." The new Hydrocarbon Law that stems from the 2013 Energy Reform states in Article 96 that "The activities of Exploration and Extraction are considered to be of public interest and order, and as such they will have preference above any other, which implies the use of the surface or the subsoil of the land which are subject to them. The Federation, the government of the states and the Federal Districts, the municipalities and the delegations, will contribute to the development of Exploration and Extraction projects, as well as those for the Transportation and Distribution by pipeline and for Storage, through procedures and coordination methods which streamline and ensure the granting of the permits and authorizations in their area of competence."[3]

The focus areas lie in two contrasting geographical settings that have impacted not only their culture and history but also their socio-economic development: La Huasteca region and the Northeastern Mexico region. The La Huasteca region covers the central and northern parts of the state of Veracruz and the easternmost parts of the states of Puebla, Hidalgo, and San Luis Potosi. This region embraces the Tampico-Misantla Basin, where first geologic exploration for petroleum took place and a full oil economy developed in Mexico at the beginning of the twentieth century. The intensity of the exploration and production of its petroleum resources during the first half of the twentieth century brought about a tremendous transformation in local social structures and land use that produced negative social and environmental effects (Santiago, 2006).

The Northeastern Mexico region encompasses the Burgos Basin, the Mexican part of the Maverick Basin, and the Sabinas Coal Basin. This region lies in a dry and semiarid

[3]Translation of the Mexican new Hydrocarbons Law, taken from Mayer Brown, 2015.

region that embraces some of Mexico's most industrialized states. Historically, the economy of these states has been driven by the commercial, agriculture, mineral, and industrial sectors, which have developed around the areas of the La Laguna region and the city of Monclova (States of Coahuila and Durango), Monterrey area (State of Nuevo Leon), the coastal zone of Matamoros-Tampico (State of Tamaulipas), and the Mexico-U.S. border cities. The petroleum industry began in 1945 with Mexico's first commercial gas discoveries in the Burgos Basin.

WATER RESOURCES

La Huasteca Region

According to the Comisión Nacional del Agua de Mexico (CONAGUA, 2015a) the La Huasteca region is drained by currents that can be grouped into two hydrological regions: Pánuco, and northern Veracruz (Figure 62). In these regions, currents all run down to the Gulf of Mexico from the highest mountains of the Sierra Madre Oriental located in eastern Puebla, Hidalgo, and San Luis Potosi. As a result, the La Huasteca region lies in a region of Mexico where one of the highest hydrological capacities are found. The data indicate that run-offs in this part of Mexico represent 11% of the total national surface waters. The average annual rainfall in this region is 1,130 mm, which is twice as much as the average precipitation in the rest of the country (CONAGUA, 2015a) (Figure 63). With respect to groundwater, the CONAGUA (2015a) reports that the four states in La Huasteca contain 64 of the 653 aquifers found in Mexico.

Although there are no water supply problems in La Huasteca, paradoxically the States of Veracruz and Puebla are under pressure and facing problems such as mismanagement, lack of regulations, pollution, and a bimodal climate pattern, with periods of heavy rain causing floods in the lower parts of the region, and yearly droughts (CONAGUA, 2015a).

All of these problems have led to inter-municipal conflicts because the largest cities consume most of the water supply and consequently pollute the springs of some villages that are located in the lower parts of the basins. For example, in some drought periods, the inhabitants of the highlands have threatened to close the valves of dams in exchange for resources to build small roads to population centers located in the most remote parts of the mountains (Paré, 2009).

The Northeastern Mexico Region

With regard to pluvial precipitation, the information of CONAGUA (2015a) indicates that the focus areas for shale resources in the northeastern states are located in two clearly distinct regions: a western area that encompasses the Coahuila State and an eastern area that covers the Nuevo Leon and the Tamaulipas States. Coahuila is one of three driest states in Mexico and includes a desert region with an average of 100 to 200 mm of rainfall per year and a dry region with an average of 300 mm per year (Figure 63). The Sabinas Coal Basin lies at the boundaries of the two regions. In the eastern area, average pluvial precipitation is 589 mm per year (CONAGUA, 2015a), and the climate becomes a little more humid towards the Gulf of Mexico. The Sabinas Coal Basin and the western part of the Burgos Basin are in the Rio Bravo/Grande Basin, which has as tributaries the Conchos, Pecos, Devils, Salado, and San Juan rivers (Figure 62). This basin has played a significant role in the agricultural development of Texas, Coahuila, Nuevo Leon, and Tamaulipas. However, high population growth on both sides of the border has led to this basin and their aquifers to experience supply shortage and high contamination problems. Along the border region, the Rio Grande supplies water for drinking and irrigation uses for more than 6 million people and 2 million acres of land (IBWC, 2015).

Another source of water stress is in the metropolitan area of Monterrey, which is home to 85% of the total population of the State of Nuevo Leon. Surface waters that flow from the Sierra Madre Oriental supply 60% of Monterrey's water needs; and the rest comes from aquifers (SADM, 2015). In 2011, the Federal Government, along with the State Government launched the plan of building a water pipeline to bring water from the Panuco River located in the Veracruz-Tamaulipas border into Linares, Nuevo Leon. This water pipeline is 372 km long and 84 inches in diameter. In Linares, it will be connected to the Cerro Prieto-Monterrey water pipeline. This project is named Monterrey VI, and it is planned to move 5,000 liters per second (CONAGUA, 2015b). The construction of the pipeline began in 2014 in the middle of social controversy due to its cost (~2.9 billion dollars), lack of transparency in the auction process, and environmental concerns (Martínez Chacón, 2015). The opposition to the project includes some influential commercial and industrial sectors of the State of Nuevo Leon, which are concerned about the debt that the state incurred to carry out the project. Environmental groups opposed to hydraulic fracturing claim that this pipeline could be used for shale gas extraction (Cervantes, 2015). Hence, this issue became a key factor in the recent election for Governor. The winner had the cancelation of the project as one of its main campaigns promises.

Figure 62: Map showing the hydrologic regions in Mexico and the focus areas (modified from CONAGUA, 2015a).

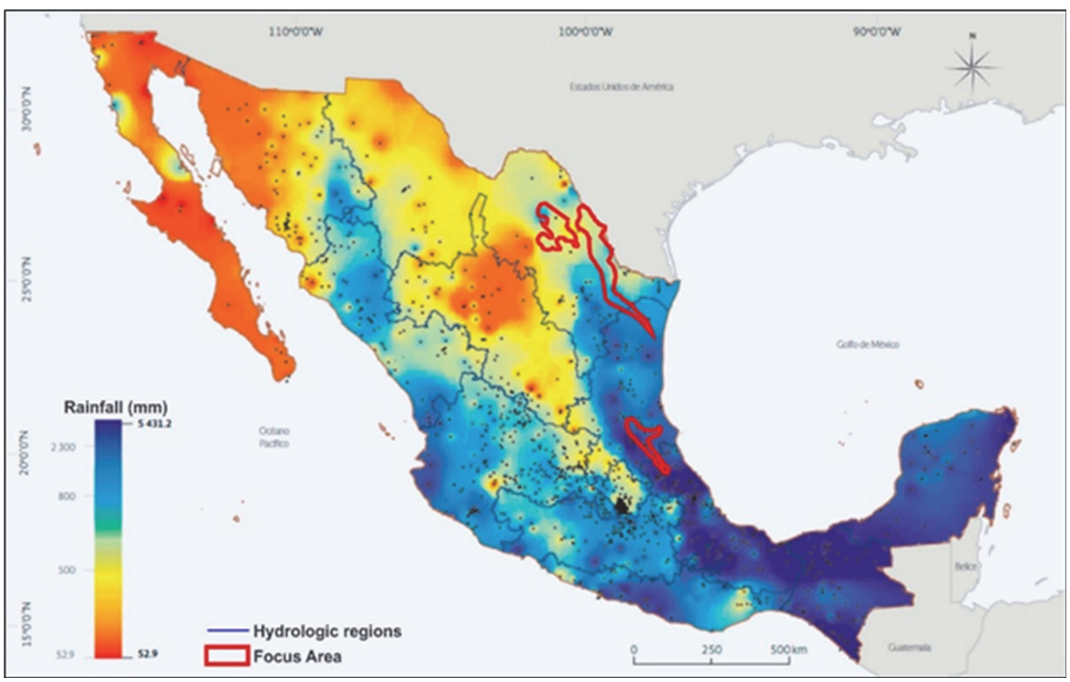


Figure 63: Map showing the annual rainfall precipitation in 2013 and the focus areas (modified from CONAGUA, 2015a).

POPULATION FACTS

La Huasteca Region

La Huasteca is characterized by its high pre-Hispanic identity. Between 50% and 90% of the people are indigenous, with a variety of languages, cultures, and social organization (Santiago, 2006). The Mexican ethnologist and anthropologist Bonfil Batalla (1996) argues that indigenous communities have a "complex" and "harmonious" relationship with the natural world. Nowadays, Veracruz and Puebla are ranked as the third and the fifth in population, with 7.9 and 6.0 million people respectively, which represent 12% of the total population of Mexico (~118 million). According to CONAGUA (2015a), regarding population density, these two states are ranked as the eleventh and seventh, with 110 and 177 people per km^2, respectively. Hidalgo and San Luis Potosi both have a quasi-equal population of 2.8 and 2.7 million people respectively, with a population density of 135 and 44 people per km^2, respectively (Table 13 and Figure 64).

Of the four aforementioned states, more than half of their population live in urban centers, and only in the state of Veracruz agriculture and livestock dominate the economy. The broad socio-cultural diversity of La Huasteca is reflected in the high number of counties or municipalities of Veracruz and Puebla, which are ranked as second and third with 217 and 212 municipalities, respectively (CONAGUA, 2015a). These two states represent 17% of the total Mexican municipalities.

The Northeastern Mexico Region

The Northeastern Mexico region has a less pre-Hispanic identity than the La Huasteca region. Indigenous heritage is present only in some regions of central Coahuila, western Nuevo Leon, and north and south Tamaulipas (Comisión Nacional para el Desarrollo de los Pueblos Indígenas, 2006). Therefore, in terms of culture, social organization, and languages, this region is different from the La Huasteca region. Nowadays, Tamaulipas, Nuevo Leon, and Coahuila are ranked as the thirteenth, eighth, and sixteenth in population, with 3.4, 4.9, and 2.9 million people, respectively, which together represent 10% of the total population of Mexico. In terms of population density, these three states are much less densely populated than those states in La Huasteca (Table 14 and Figure 64), and ranked as the twenty-second, fifteenth, and twenty-seventh, with a respective population of 43, 77, and 19 people per km^2 (CONAGUA, 2015a).

Another notable difference is that more than 90% of the population in the northeastern states live in urban centers, and they are among Mexico's most industrialized states. The lesser socio-cultural diversity of these three states is reflected through the considerably smaller number of municipalities in Tamaulipas, Nuevo Leon, and Coahuila, which are ranked as eighteenth (43 municipalities), sixteenth (51 municipalities), and twentieth (38 municipalities), respectively (CONAGUA, 2015a). These figures represent the 5% of the total Mexican municipalities.

State	Capital	Population 2013	Urban (%)	Rural (%)	Area (km^2)	Population Density (people/km^2)	# of municipalities	% of poverty (2014)	Average annual rainfall (mm/year)	# of aquifers
Veracruz	Xalapa	7,923,198	65%	35%	71,820	110	212	58%	1,617	18
Puebla	Puebla	6,067,607	78%	22%	34,290	177	217	65%	1,040	6
Hidalgo	Pachuca	2,806,334	60%	40%	20,846	135	84	54%	829	21
San Luis Potosí	San Luis Potosí	2,702,145	68%	32%	60,983	44	58	49%	1,040	19
Total		19,499,284			187,939		571			64

Table 13: Geographic context of the La Huasteca region (data from CONEVAL, 2015; CONAGUA, 2015a).

State	Capital	Population 2013	Urban (%)	Rural (%)	Area (km^2)	Population Density ($people/km^2$)	# of municipalities	% of poverty (2014)	Average annual rainfall (mm/year)	# of aquifers
Nuevo León	Monterrey	4,941,059	96%	4%	64,220	77	51	20%	589	23
Tamaulipas	Ciudad Victoria	3,461,336	90%	10%	80,175	43	43	38%	760	14
Coahuila	Saltillo	2,890,108	90%	10%	151,563	19	38	30%	386	28
Total		11,292,503			295,958		132			65

Table 14: Geographic context of the Northeastern Mexico region (data from CONEVAL; CONAGUA, 2015a).

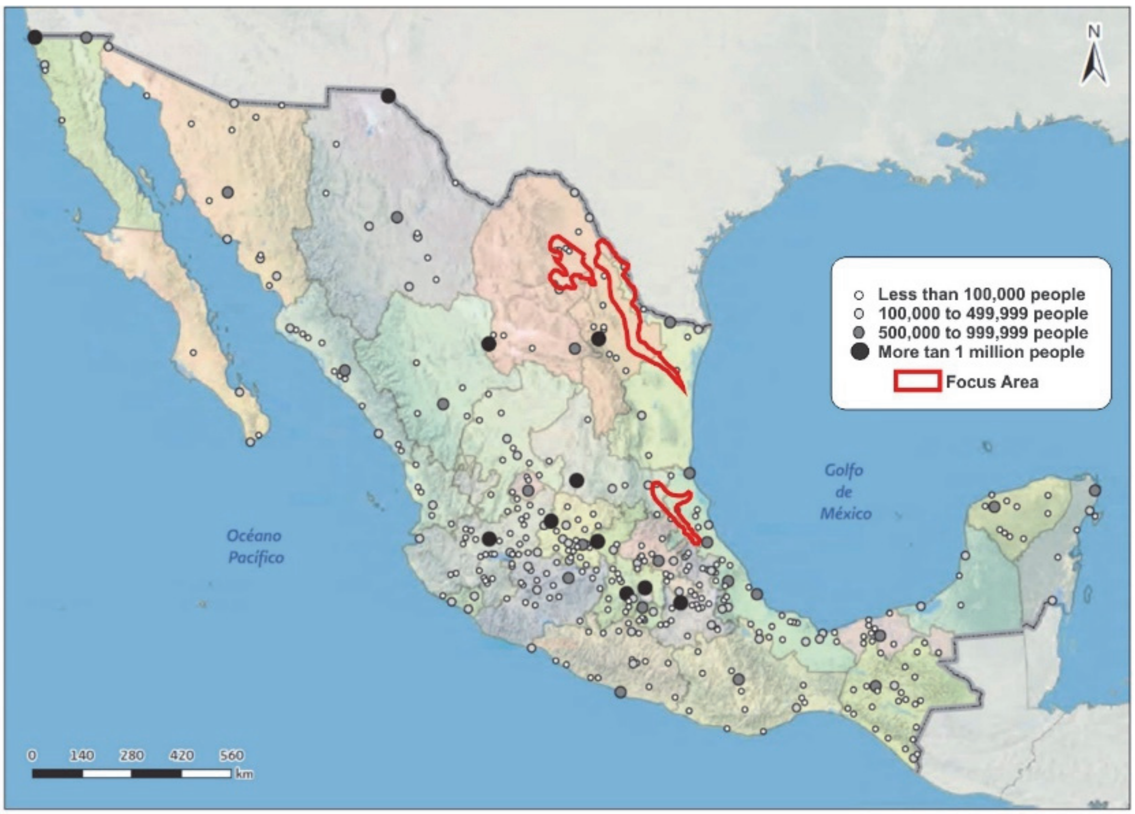


Figure 64: Map showing the largest population centers and the focus areas in Mexico (modified from CONAGUA, 2015a).

Socio-Economic Conditions

La Huasteca Region

Mexico is characterized by great economic inequality. La Huasteca is not exception. However, pockets of high income are generated by agriculture, livestock, and petroleum production. Regarding the Human Development Index (HDI), applied by the United Nations Development Programme (UNDP), in 2013 Mexico ranked as seventy-first 71 (0.756) out of 187 countries with comparable data. Norway ranks first with an HDI of 0.944 while the U.S. ranks as fifth with an HDI of 0.914 (UNDP, 2014).

The Consejo Nacional de Evaluación de la Política de Desarrollo Social (CONEVAL) applies a methodology to measure poverty that suits Mexico's characteristics while still following international standards. According to this methodology, in 2014, the four states that comprise La Huasteca are among the thirteen poorest states in Mexico. Puebla ranks fourth with 65% of the population living in poverty conditions, Veracruz seventh with 58%, Hidalgo eighth with 54% and San Luis Potosi thirteenth with 49% (CONEVAL, 2015).

The Northeastern Mexico Region

According to CONEVAL (2015), the State of Nuevo Leon presents the lowest percentage of poverty in Mexico with 21%. Tamaulipas is ranked twentieth (39%) and Coahuila thirty-first (28%). Even though these percentages are high, they contrast with the States of the La Huasteca region, which are among the poorest States of Mexico.

Road Infrastructure

La Huasteca Region

Despite its richness in natural resources, La Huasteca does not have a good road infrastructure. The main roads are two lane and connect Mexico City with Tuxpan, Poza

Rica, and Tampico. Other important roads are two lane roads, which connect Tampico with San Luis Potosi and Mexico City with San Luis Potosi (Figure 65). A new toll highway between the City of Mexico, Poza Rica and Tuxpan was completed in 2014. The rest of the roads are local roads, some of which are not paved, especially those located in the mountains. The shortage of road infrastructure will be a serious challenge for shale development, which requires heavy truck traffic for hydraulic fracturing. The construction of new roads will require a good relation between companies and local communities to win collaboration and to avoid disruption to petroleum activities. In 2014, Gustavo Hernández, current Director of Operations of PEMEX Exploration and Production revealed that the company was not able to reach the expected production in the southern region because local communities did not permit access to well sites (Robles de la Rosa, 2015). Santiago (2006) extensively documents the tensions inherent in the relationships between the oil industry and local communities when La Huasteca became the center of Mexico's oil industry at the beginning of the twentieth century. DeGolyer points out that when he worked in La Huasteca with the El Aguila Oil Company, local communities cooperation was of the utmost importance to carry out exploration works (Tinkle, 1970).

The Northeastern Mexico Region

Historically, northeast Mexico has been an important transportation hub because its proximity to the U.S.–Mexico border and the nearness of two important ports of the Gulf of Mexico: Matamoros and Tampico (Figure 65). Thus, the industrial development of this region of Mexico has led to a relatively good infrastructure. Most of the roads are paved; it has six of the most important airports in Mexico, and it is one of the regions with best railway connections.

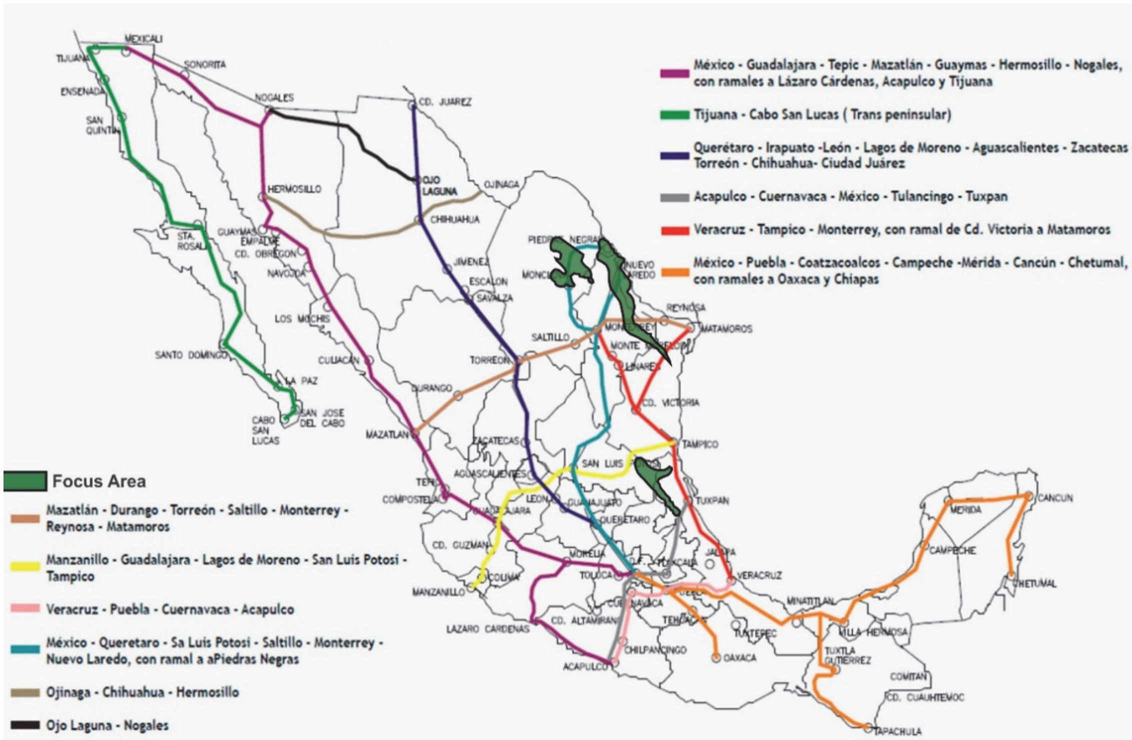


Figure 65: Map showing the main roads in Mexico and the focus areas (modified from Gobierno del Estado de Chihuahua, 2007).

PIPELINE INFRASTRUCTURE

Natural Gas

As a result of the expected growth rates in future natural gas production, one of the aims of the new Energy Reform is to boost the pipeline capacity given the fact that the present PEMEX gas pipeline infrastructure is utilizing 97% of its capacity. The natural gas transportation network in Mexico consists of 13,890 km of pipelines with an average volume of 37,536.4 MMcfd. 65% (9,043 km) of the total network belongs to PEMEX and the rest (4,847 km) are property of private companies (SENER, 2014a) (Figure 66).

Two milestone developments changed the natural gas market in Mexico in the last twenty years. The use of more efficient and lower-emission combined-cycle power plants to produce electricity, which began to substitute for old fuel-oil plants in the 1990s; and the Constitutional amendment in 1995, which granted private companies the permission to transport, store, distribute and trade natural gas. As a consequence of these changes, between 2003 and 2013, demand for natural gas grew 4% per year (SENER, 2014a) and PEMEX increased its budget and activities for dry gas exploration.

As it was mentioned in Chapter 2, in 2009, PEMEX produced 7,031 MMcfd, a historical record and since then the production has declined. Therefore, natural gas imports increased at an average annual rate of 19% to reach 2,516.6 MMcfd in 2013. Of these, 761.1 MMcfd were LNG received in three LNG terminals: Altamira in northeast Mexico, Manzanillo in western coast, and Ensenada in Baja California. The rest was delivered via pipeline from the U.S. (SENER, 2014a). The pipeline imports from the U.S. has continued to increase; more pipeline capacity is under construction at the time of writing.

Hence, eighteen new projects are under various stages of development or announced in addition to four projects that were already under construction or in operation (SENER, 2013b). These four projects will allow imports from Texas and Arizona to Mexico and consist of 1,151 km with a transportation capacity of 2,870 MMcfd. The Tucson, Arizona to Sásabe, Sonora pipeline started operation in 2014 in its first segment with a capacity of 770 MMcfd. The rest of this project is planned to be completed by the end of 2016. The other three projects add up to 1,054 km of pipeline with a capacity of 2,100 MMcfd from Agua Dulce, Texas to the Monterrey metropolitan area and the central States of Mexico. The first segment (Los Ramones Phase I from Agua Dulce, Texas to Monterrey, Nuevo Leon) started operation in 2014 and the last two segments are expected to be completed by December 2015 (Figure 66).

The eighteen new projects are expected to be done between 2016 and 2018 and will have a total length of 6,449 km, with an average transportation capacity of around 1,200

MMcfd (SENER, 2014a). Of these, five pipelines are cross-border with the U.S. and one to export to Guatemala (Figure 66).

With the accomplishment of the gas pipeline infrastructure plan, the shale focus areas of the Northeast Mexico and La Huasteca regions will be near new and old mainlines, which will reduce the need for investment in such midstream facilities in order to develop shale resources. There will still be a large need for gathering pipelines at the field level as well as larger-diameter connecting lines. Given that there is only one gas processing facility near the northeast focus area (near the Texas border) and two facilities near La Huasteca, it is possible that more investment will be needed in additional processing capacity in the case of successful development of these resources. However, at this point, the lack of data and uncertainty about existing data (e.g., the exact location of "sweet spots," possible production levels, the raw composition of the natural gas) do not permit developers to ascertain the need for new pipeline and/or processing capacity.

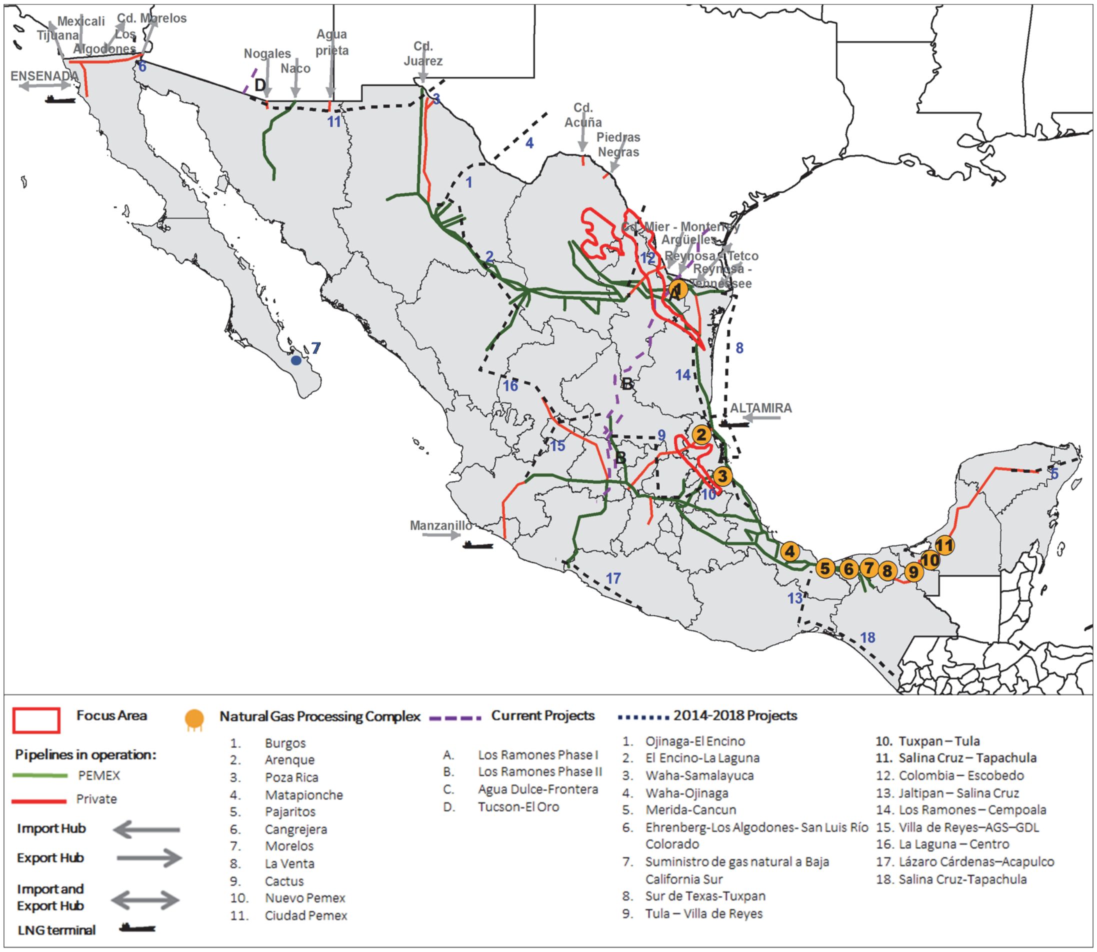


Figure 66: Mexican natural gas current infrastructure and current and future projects to increase the capacity (SENER, 2013b; PEMEX, 2014c; Salazar Diez de Sollano, 2015).

Oil

PEMEX is the only owner of the oil pipelines that make up a network of 5,223 km (Figure 67) (SENER, 2014b). This network connects the main producer regions located in southeast Mexico with the six refineries that exist in the country and with the Cangrejera petrochemical center located in the southern part of Veracruz (Figure 67). The last refinery was built in 1979 in Salina Cruz, Oaxaca, and since 1998 the refining capacity of these centers has not changed. No plans exist to increase oil refinery and pipeline capacity.

Because shale oil and gas activities require drilling many wells, there will be a need for a lot of investment in gathering and processing, and possibly simple refining near the production areas. In the case of success of both conventional and unconventional resource development as a result of the energy sector reforms, the recent decline in oil production can be reversed, and future production may surpass historical levels. In that case, Mexico may need new midstream and downstream capacity. Otherwise, the decline in conventional production (as discussed in Chapter 2) has probably freed up some capacity in the existing system, parts of which are relatively close to the two focus areas for unconventional development. Still, much of these investment needs cannot be identified with much accuracy at this time given the limited amount of data available publicly and a wide range of uncertainty associated with these data. As in the case of shale resources, the exact location of sweet spots, the pace of development, peak production rate and composition of fluids produced, among other factors, will determine the needs for midstream and downstream assets.

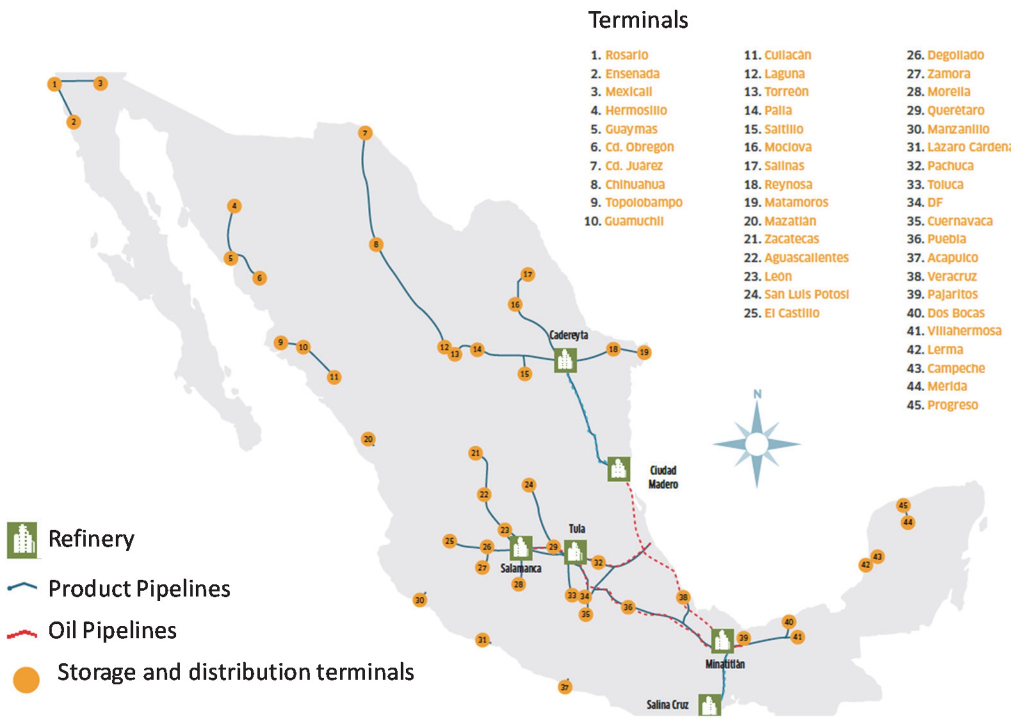


Figure 67: Mexican refinery and oil and product pipelines infrastructure (modified PEMEX, 2014c).

Legal and Regulatory Frameworks

Once PEMEX reported early results of its first shale gas wells, the Federal Government began to forecast total natural gas production including shale gas. These projections have not been consistent for unknown reasons. In 2012, the SENER had a scenario with total natural gas production for 2026 of 8,958 MMcfd, 1,343 MMcfd of which would be produced by the Mexican extension of the Eagle Ford play. SENER (2013a) production forecast for 2027 was 6,849 MMcfd, 178.9 MMcfd of which would be produced by shale gas plays. SENER (2014a) considered that with the new Energy Reform, Mexico could have total natural gas production of 8,004 MMcfd by 2018, and 10,540 MMcfd by 2028. In this last forecast, SENER (2014a) considers that PEMEX would produce 6,261 MMcfd, and private firms 4,279 MMcfd. Of the total production in 2028, about 9% (925 MMcfd) would be produced by shale plays. In this scenario, PEMEX's 2014-2018 business plan (PEMEX, 2014b) called for drilling 324 exploratory wells to confirm the shale gas and oil potential of the country. According to SENER (2014b), the investment in shale exploration will begin to grow in 2018 in such a way that by 2026, one-third of the total investment in exploration of PEMEX will be allocated in shale plays.

Implementing Regulations

Despite the above expectations, the first two bidding rounds in July and September 2015 were partially disappointing. The timing was probably not the best given the low level of oil prices since October 2014 and announcements of capital budget cuts by almost all international oil and gas companies. These bidding rounds did not focus on unconventional resources but after the results of the first one, Pedro Joaquín Coldwell, Mexico´s Energy Secretary announced that the unconventional oil and gas resources bidding plan "has been frozen" and "suspended for future evaluation" (El Economista, 2015; Energy Intelligence, 2015). The "2015-2019 Hydrocarbon Exploration and Extraction Bidding Plan" (SENER, 2015b) does not include an update of the expected investments in unconventional or the number of wells to be drilled in the future.

At this point, some considerations must be offered. Given that only eight wells have been drilled in the Eagle Ford Group since 2011, PEMEX's target of 324 exploratory wells between 2014 and 2018 appears aggressive. Outside the U.S., most active shale development has been taking place in Argentina and China. These countries have drilled about 300 and 200 wells, respectively since 2013. Given these experiences, PEMEX target seems achievable from the perspective of logistics; but it is important to realize that both countries have a history of allowing international companies to explore and produce oil and gas in their basins, and particularly encouraged their participation in the case of shale resources. Chevron, Apache, and others are active in Argentina; Shell was a driver in China but recently pulled out, partially owing to disappointing results of first wells completed and partially owing to Shell's changing strategy in a period of low oil prices. Most analysts had high expectations in Poland, which offered attractive investment frameworks for international companies; but, over time, disappointing results from test drilling, challenging geology (not enough brittleness to reach commerciality), logistical constraints (lack of infrastructure and permitting delays), and market dynamics led to companies such as ExxonMobil and Marathon exiting the country (Naumann and Philippi, 2014).

Mexico's close proximity to the U.S. Gulf Coast where most of the logistical infrastructure and supply chain for the shale industry is concentrated can be an advantage, but legal and regulatory frameworks must be appropriate to attract investment from these companies. Mexico is trying to overcome a long history of not allowing private companies, especially international ones, in oil and gas exploration and production. The sector has been changing as the new reforms are being implemented but, there is still work to be done in terms of developing a consistent legal and regulatory framework.

In recent years, Mexico has made efforts to demonstrate more transparency in government-related affairs with the creation of the Auditoría Superior de la Federación and the Instituto Nacional de Transparencia, Acceso a la Información y Protección de Datos Personales (INAI). Mexico's performance on the Resource Governance Index is "satisfactory" since it is ranked sixth among 58 countries by the Revenue Watch Institute (2013). In terms of institutional and legal setting, reporting practices, and safeguards and quality controls, Mexico averages 82 out of 100. However, in terms of enabling environment, the results are partial due to a low ranking in corruption and the particularly low ranking rule of law. A further step ahead in order to be in the right direction might be the announcement made by the Secretary of Economy in January 2015 to launch Mexico's candidacy to the Extractive Industries Transparency Initiative (EITI) (Secretaría de Economía, 2015). The implement of the EITI's standards and fulfillment of its principles would be a compelling message to external investors that the rule of law can be abided by in Mexico.

In the case of unconventional resources, the delay of these assets from future bidding rounds appears to be a reasonable decision. The global experience with assigning unconventional resources to companies is relatively new; Mexico can further analyze these experiences in Argentina, China, Poland, and elsewhere to develop rules and regulations commensurate with estimated resource quality while complying with global best practices in terms of transparency and the rule of law. The U.S. experience is not readily translated to other countries given the significant differences in commercial frameworks, including the ownership of minerals, which also has relevance for Mexico as discussed next.

Mineral and Land Ownership

In the U.S., private landowners own the mineral rights under their land, unless those rights have been legally severed at some point in time (e.g., when land was sold to a new owner, with the original owner keeping the mineral rights). This is fairly unique in the world. Combined with a very competitive environment for exploration and production, private mineral ownership motivates rapid resource development. In Texas and the U.S., land leasing for energy projects is an opportunity for landowners to generate profits from the resources in their land. The lessors offer the right to extract these resources in return for a share of the profits, i.e., royalties. Private mineral ownership structure and competitive industry, combined with other factors favorable to business, has made Texas the leader in total energy production in the U.S., primarily crude oil and natural gas, as well as the top wind-powered generation state (EIA, 2014).

In Mexico, like the rest of the world, the ownership is conferred to the Nation owing to several historical reasons, including the Spanish legacy on the Mexican Constitution of 1917. From this fundamental principle, the State grants four land tenures: private, communal (rural villages in which land is held communally), ejidal (collective holdings granted by the State under the Agrarian Reform of 1915), and national territories (areas of public interest). The 1992 Constitution amendment allows the ejidatarios (the owners of the Ejidos) to lease or sell the ejidal land or the land plot through a two-thirds vote of their General Assembly.

In Mexico, there are 31,785 Agrarian Cores (ejidal and communal lands) out of which 29,442 are ejidal lands, and 2,343 are communal lands (Registro Agrario Nacional, 2015a). More than a half (51%) of Mexico's territory is occupied by these Agrarian Cores (Figure 68). The states that form the La Huasteca region comprise 24% of Mexico's Agrarian Cores (7,536) (Table 15). In these areas, there are about 1,159,000 peasants whose tenure is held through this communal system. In the northeastern states, there are 2,894 Agrarian Cores representing 9% of Mexico's total and includes roughly 272,000 peasants. The ejidatarios has three different uses for their land: the first type is for human settlement, and the last two correspond to parcel lands (land that has been split among the ejidatarios and which can be exploited individually or collectively), and common land use. These last two types can be for agriculture, livestock, forestry, or other uses. According to Procuraduría Agraria (2010), 69% of the total land use in agrarian cores correspond to common land use, 30% to parcel lands, and 1% to human settlement; and the main activities are agriculture and livestock (Table 15).

The unique historical and multicultural roots of Mexico represent at least two relevant considerations regarding the implementation of shale projects. First, Mexico does not have an official language as many countries of the world do. Therefore, there is not an official translation to English or any other language of the Hydrocarbons Law or other any other Law. Hence, any translations may cause different opinions regarding the content and scope of the law; that may lead to well-justified controversies. Second, at the beginning of this century the "Reforma Indigena" was enacted. This Reform recognizes at Constitutional level the right of indigenous communities to take autonomous decisions regarding several aspects such as: social, political, and economical organization; solution of internal conflicts; election of authorities; maintenance and improvement of the natural environment; preservation of the integrity of their lands; and preferential use and enjoyment of the natural resources that exist within their lands. This reform also recognizes the responsibility that authorities have to drive the regional development of the indigenous zones with the purpose of strengthening and improving the local economies and the standards of living. Therefore, the application of the Hydrocarbon Law in zones where indigenous communities exist, despite being considered as legally and constitutionally strategic areas, will depend on the respect for the rights of those communities. Otherwise, not only legal but also social conflicts may delay projects or render them unfeasible (excerpt from a written communication of Raúl García Herrera, Attorney at Law in Guerra González y Asociados).

The focus area located in La Huasteca is mostly occupied by Agrarian Cores; whereas in the focus areas located in the Northeastern Mexico region, the density of the Agrarian Cores is considerably less (Figure 68). The Hydrocarbon Law that stems from the 2013 Energy Reform establishes the terms under which companies and landholders must negotiate the right-of-way to access and work on the resources in the subsoil of privately owned lands as well as Agrarian Cores. Nevertheless, Payan and Correa-Cabrera (2014) state that the question is whether this law will be enough to prevent potential resistance from landowners "given the large symbolic nature of land tenure in Mexico's convoluted history." These authors point out that indigenous communities may not appreciate the concept of land cession at market value.

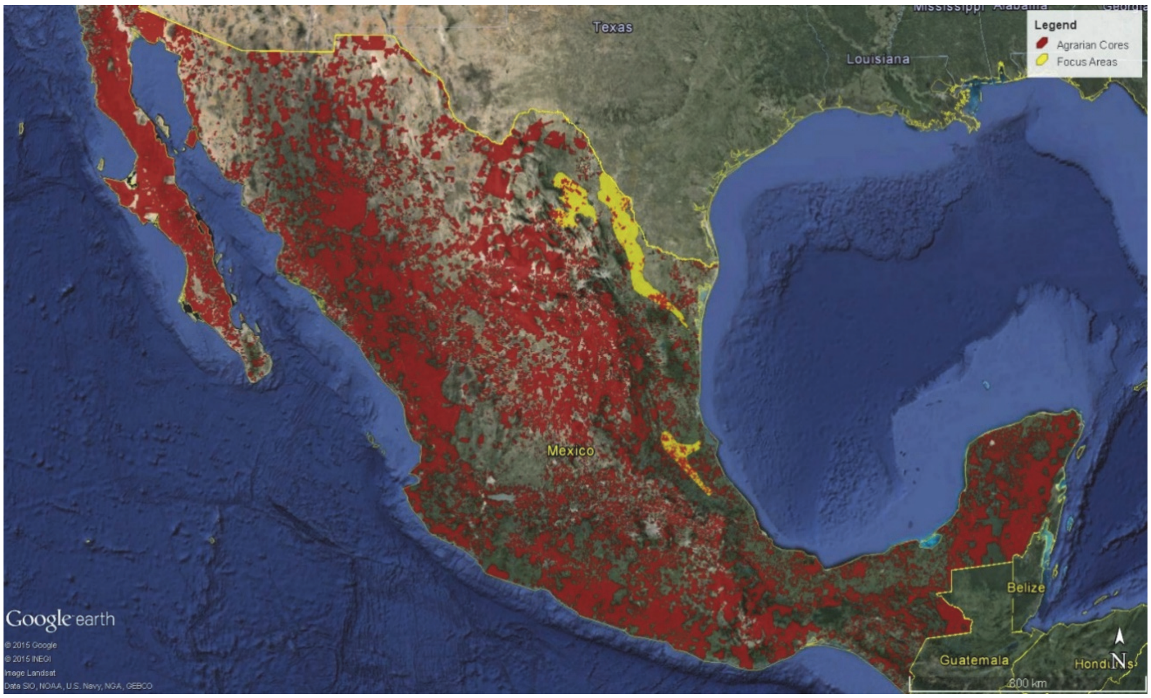


Figure 68: Map showing the area occupied by Agrarian Cores in Mexico and the focus areas (made with data from Registro Nacional Agrario, 2015b).

State	Total Area (km^2)	Area		Agrarian Cores	Main land use	
		km^2	%		Common Land Use	Parcel Lands
Veracruz	71,820	28,681	40%	3,725	Forestry (34.9%)	Agriculture (51.8%)
Puebla	34,290	15,419	45%	1,196	Livestock (44.3%)	Agriculture (91.6%)
Hidalgo	20,846	9,452	45%	1,171	Livestock (33.6%)	Agriculture (96.7%)
San Luis Potosi	60,983	40,686	67%	1,444	Livestock (69.5%)	Agriculture (75.7%)
Total				7,536		

State	Total Area (km^2)	Area		Agrarian Cores	Main land use	
		km^2	%		Common Land Use	Parcel Lands
Nuevo Leon	64,220	18,651	29%	608	Livestock (62.3%)	Agriculture (56.8%)
Tamaulipas	80,175	25,819	32%	1,395	Livestock (62.4%)	Agriculture (53.6%)
Coahuila	151,563	62,258	41%	891	Livestock (78.2%)	Livestock (62.7%)
Total				2,894		

Table 15: Characteristics of the Agrarian Cores in the states occupied by the Focus Areas (data from Registro Agrario Nacional, 2015a).

The Hydrocarbon Law assigns the preference to the Exploration and Extraction activities above any other (Article 96). In terms of use and occupation of land surface, Article 100 states: "the compensation, the terms and conditions for the use, enjoyment or affection of the lands, goods or rights necessary to carry out the activities of exploration and extraction of hydrocarbons will be negotiated and agreed between the owners or holders of said lands, good or rights, including real or communal rights, and the Assignation Holders or Contractors. In the case of private property, the acquisition may also be agreed." Article 101 states that Landowners will be eligible to be compensated as follows:[4]

a. "The payment of the affectations of goods rights other than the land, as well as the provisions for losses and damages, which could be suffered as a result of the project to be developed, calculated on the basis of said property's regular activity;
b. the rent for the occupation, easement or use of the land;
c. for a project that reach the commercial extraction of Hydrocarbon phase, a percentage of the revenues accruing to the Assignation Holder or Contractor in the project in question, after deducting the payments that must be made to the Mexican Petroleum Fund for Stabilization and Development, subject to the provisions of the last paragraph of this article."

In addition, "the percentage to which the preceding paragraph refers may not be less than zero point five nor more than three percent in the case of Non-Associated Natural Gas, and in all other cases it may not be less than zero point five percent nor more than two percent, in both cases for the benefit of all the owners or right holders concerned."

[4] Translation of the Mexican new Hydrocarbons Law, taken from Mayer Brown, 2015.

Key Findings

In terms of geography, water resources, population facts, socio-economic conditions, and road infrastructure, the focus areas are in regions that present specific and serious technical and operational challenges for companies, including water shortage or mismanagement of water resources, insufficient road infrastructure, and the ability to deal and negotiate with people with strong cultural and social roots. Therefore, interested parties will need to shape a technological and management strategy adapted to each specific geographical condition to overcome these challenges and to build a reliable reputation in the communities. The international oil and gas industry is well-versed in overcoming these challenges given decades of experience around the world in some of the most challenging environments. Increasingly, host communities are integral to sustainable solutions. However, this experience is almost exclusively in the conventional resource sphere. Development of shale resources presents additional challenges given the density of drilling and hydraulic fracturing supply chain needs. Also, most companies experienced in the U.S. shale are smaller independents with little or no international exposure. If smaller independents sign up for developing unconventional resources in Mexico, it will be important for them to seek early local assistance to address these challenges.

Regarding mineral and land ownership, although the new law provides compensation for the landowners and a process to negotiate, companies should consider that prioritization of energy sector activities over any other economic activity has raised concerns among civil, environmental, landowner, and indigenous groups and communities about the impacts of this law. The companies will have the challenge to maintain, and possibly enhance, the quality of life in communities by exploring ways to avoid disturbing the environment and social fabric, reinforcing confidence by sharing information about the whole exploration and production process, all with corporate social responsibility to make possible tangible benefits to the communities through the support of other economic activities that encourage the human capital development of Mexico.

Companies must be aware of historical and multicultural roots of Mexico and some of the recent conflicts between the government and local communities, to avoid social and legal conflicts. At first glance, it seems unlikely that Agrarian Cores may impede federal initiatives, however, indeed it may be a significant challenge. A good example of this challenge is the cancelation of the project for a new airport in Mexico City. In 2001, former president of Mexico, Vicente Fox, announced the construction of a $2.3 billion pesos new Mexico City international airport in Texcoco in Estado de Mexico. The land would be acquired by the expropriation of 1,391 hectares of farmland from more than 4,000 ejidatario's families (Díaz, 2014). However, the ejidatarios rejected the compensations (~US$3,000 per hectare), organized the "Frente del Pueblo en Defensa de La Tierra," and protested violently with machetes and sticks against the project. After nine months of conflicts, in 2002, Vicente Fox announced the cancelation of the project and another plan for a new terminal in the current Mexico City international airport.

Private ownership of mineral rights in the U.S is fairly unique in the world and has been a key non-geological factor for the success of the shale industry. A very competitive environment for exploration and production, and the extensive development of a pipeline national network have played a pivotal role as well. Obviously these conditions do not exist in Mexico; hence, the way Federal Regulators manage the right-of-way for roads and pipeline construction, operation, maintenance, and safety will be crucial. Land use regulation for hosting drilling without disturbing the social fabric will be challenging as well.

Mexico is making considerable efforts to reinforce its pipeline capacity, however, it has a road ahead in terms of extensive national pipeline network to ensure supply. The uncertainty about pipeline takeaway capacity and composition of produced fluids in case of success in Mexico should lead interested parties to develop methodologies and tools to adequately determine and clarify the expected hydrocarbon, the values of original gas and oil in place, the technically recoverable resources, recovery factors, decline rates, and the economic viability of the focus areas they have access. More likely infrastructure will be built as the new fields will be developed; hence, an outstanding infrastructure planning is vital to avoid any lag in the process.

CONSIDERATIONS FOR DEVELOPMENT OF A SUCCESSFUL SHALE INDUSTRY IN MEXICO

The unique U.S. conditions discussed in previous sections have permitted the development of an efficient supply chain in the shale industry, where behind the scenes are hundreds of operators and service companies competing to improve costs and returns. Since the late 2000s, about 30,000 shale wells a year were drilled in the U.S. (drilling has slowed down considerably since the natural gas price collapse in 2008 and oil price collapse in 2014), starting primarily with the Barnett play in North Texas, followed by Fayetteville, Haynesville, Marcellus, Eagle Ford, and Bakken, among others. Drilling in the Eagle Ford did not really take off until 2011 (Figure 69).

In fact, the industry has been too successful for its own good. Too much natural gas was supplied before demand could be built. As a result, the price of natural gas has been very low since 2010, putting further pressure on operators to cut costs and/or move to more liquids-rich or oil locations from dry gas acreage (hence, the pick-up of drilling in Eagle Ford in 2010-11). Many operators were able to reduce drilling and completion costs, partially by drilling wells faster (e.g., via pad drilling), changing their approach to hydraulic fracturing (e.g., sequencing and number of stages, the composition of fracturing fluid) (Figure 70).

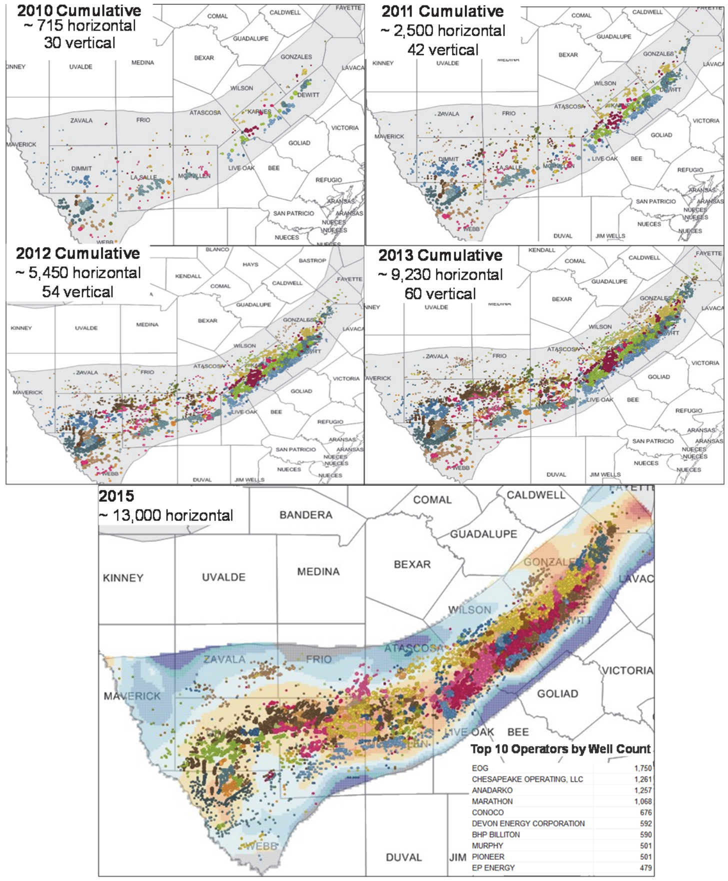


Figure 69: Eagle Ford drilling activity through time (Andrie, 2015).

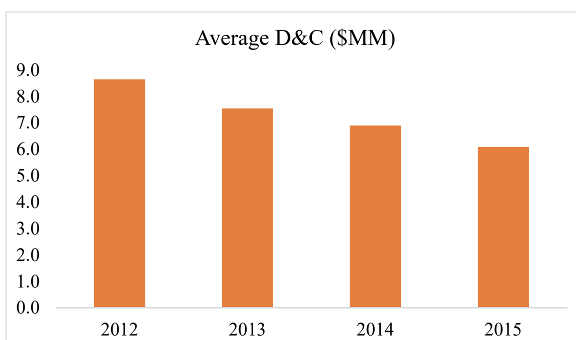


Figure 70: Drilling and completion costs efficiencies in the Eagle Ford (data from Devon Energy, 2015; EOG Resources, 2015; Cabot Oil & Gas Corporation, 2015; Marathon Oil, 2015; Encana Corporation, 2015; Chesapeake Energy 2015a and 2015b; Earthstone Energy, 2015; Swift Energy Company, 2015).

Countries where the shale potential is high need to develop a supply chain with depth and scope in terms of service providers in order to drill as many wells as needed to produce amounts of shale gas and/or oil that would make a material difference for the country. This is also the case for Mexican oil and gas production. Moreover, upstream operators need to learn from best practices in the U.S. and if appropriate, Canada and Argentina, in terms of drilling and completing wells at the lowest cost possible while maintaining good relations with local communities, without which it is difficult to sustain operations and develop necessary midstream assets to deliver production to markets.

Australia and the UK, countries interested in the assessment of their shale resources, are working on the details of possible supply chains in consonance with their particular socio-economic conditions and population facts (e.g., SARIG, 2012; Ernst & Young, 2014; Amion Consulting, 2015). Cafaro and Grossmann (2014) and Gao and You (2015) point out the shortage of decision-support tools and methodologies for a sustainable design and operation of shale gas supply chain systems, and propose optimization modeling. Cafaro and Grossmann (2014) proposed a mixed-integer nonlinear programming model to optimally determine the most economical design of a shale gas supply chain over a planning horizon comprising ten years. With this model, these authors try to determine many critical decisions to be simultaneously made in the development of a shale gas project such as the drilling and fracturing plan over the time, and the location sizing and expansion of gas processing and fractionation plants. Gao and You (2015), proposed a multi-objective nonconvex mixed-integer nonlinear programming model that allow them to conclude that in order to pursue a more environmentally friendly outcome, drilling activities should be more concentrated, unnecessary transportation links should be avoided, pipelines should be used to transport freshwater, and unnecessary gas storage is to be avoided. These tools can be useful but only if sweet spots are already identified.

Otherwise, drilling a relatively low number of wells at different locations will be necessary. The learnings from the U.S., as well as Argentina, Canada, and other countries can be useful in bypassing some of the growing pains.

In the case of Mexico, a design of a supply chain for a possible shale industry requires the understanding of challenging geology and the wise comprehension of the interplay between the federal law and the rights of indigenous communities. In particular, the following facts would play an important role for the successful implementation of a supply chain in Mexico:

- Mexico has a well-established conventional onshore oil and gas industry that is particularly strong in upstream and is expanding its pipeline network. These factors may represent an opportunity to reduce costs. However, a transparent and fair government policy and an efficient legal and regulatory framework are crucial to building and sustaining a supply chain under the new reforms with private and international participation.
- Each Mexican basin has its own geologic history that will likely lead to different learning experiences. Even within the same basin, changes in lithology can influence drilling or completion decisions. Production decline is a function of rock properties as well as completion design, which will have to be adjusted to particular geologic characteristics such as thickness and brittleness.
- Participants must work with a proactive and open attitude and with best practices to maintain a social license to operate.
- Each basin has unique geographical and infrastructure features that present challenges for operators: water management and supply; sensitive negotiation with local communities to obtain a right-of-way across the landowner's properties to construct, operate and maintain infrastructure safely.

- Reducing environmental footprint, including road, pads, pipelines, wastewater spills, methane emissions and more, are necessary to maximize the benefits of this resource to the Mexican society.
- The unique cultural and historical traditions of Mexico demand a wise understanding of the interplay between the federal law and the beliefs of indigenous communities, especially with respect to land rights. Regulatory agencies play a key role in managing land use laws to ensure drilling without disturbing the social fabric.
- An adequate level of coordination and information sharing between government agencies, including ministries and regulators, and operators, on the basis of a scientific approach are fundamental not only to shortening the learning curve but also to avoiding data opaqueness and legal and social uncertainties. This information sharing has to be done respecting privacy of commercially-sensitive data.
- A growing shale industry will demand highly trained people at various levels, from vocational training for field workers to truck drivers, and from engineers to project managers. Therefore, it is an opportunity for increasing investment in education, research, and skills development. Otherwise, the potential benefits of a new industry would not be fully captured for the benefit of the Mexican society.

Building a Mexican Shale Supply Chain

Assuming that geologic and engineering data extracted from appraisal wells permit the visualization and understanding of the economic shale potential of Mexico, and that a transparent and fair commercial framework is established, a supply chain in the Mexican shale industry may develop around two possible hubs with different characteristics (Figure 71).

A Northeastern Hub embracing the Burgos Basin, the Mexican part of the Maverick Basin, and the Sabinas Coal Basin, with physical clustering of activity, infrastructure, suppliers, and logistics in synergy with infrastructure in Texas. Assuming that 27 refineries and multiple natural gas processing plants in Texas have sufficient capacity to receive the inputs from the Mexican Eagle Ford, this could bring economic benefits to both countries and a possible replacement when the Eagle Ford reaches its production peak and starts declining.

An Eastern Hub embracing the Tampico-Misantla Basin (in the La Huasteca region), in synergy with local suppliers and the current infrastructure of eastern and southeast Mexico. The oil and gas infrastructure in east and southeast Mexico could be enough if the pace of drilling is not too fast; however, if the development speeds up, updates to current infrastructure and the construction of new natural gas processing plants and refineries will be needed.

The overlap between the two hubs is the port of Tampico, Tamaulipas, that historically has been an important trading point for the industrial and commercial activities of the northern part of the States of Veracruz and Tamaulipas. Within the Eastern hub, the ports of Veracruz and Coatzacoalcos are included. Each hub would have its particular environmental, technological, and cost challenges, and both require a rational and science-based strategy to achieve their goals. That geographic variability, water availability, landownership and the lack of road and pipeline infrastructure may be potential bottlenecks cannot be dismissed during the planning and development of petroleum activities.

The possible oil and gas supply chain in these two hubs is profiled in Tables 16A and 16B. The supply chain is shown in terms of the three fundamental segments of the petroleum value chain (upstream, midstream, and downstream), and it is non-exhaustive. Each segment is divided into succeeding time stages in which the main activities are broadly described. In the red-colored panels, key strategies, inputs, and supplies that may warrant an efficient accomplishment of them in the particular case of Mexico are highlighted. The green panels outline the critical manufacturing and service sectors that have the opportunity to get involved in delivering the inputs to the supply chain. These sectors may be international or national and may represent an opportunity to expand local economies and small businesses, if they adhere to high standards of quality and safety. The yellow panels highlight the Mexican Regulatory Agencies that have the responsibility of defining the energy policy, the bidding process, and oversee their execution with high transparency, high technical standards, and environmental compliance for tangible benefits to Mexicans (Table 17). Needless to say, the activities are more complex than portrayed here. Most of them will require its own supply chain, key strategies, risk assessments, and inputs and supplies. For example, the construction and operation of processing centers, refineries, petrochemical centers, and drilling operations are complex and large projects that will require detailed evaluation of their own. The starting point of the supply chain relies upon geology as a beacon. Companies must consider that geology is challenging in these parts of Mexico as demonstrated in Chapters 3 and 4. In addition, the law establishes that every company should submit an "exploration program" and a "development program" to the National Hydrocarbon Commission in order to be approved. With the current prices of natural gas and oil, any interested company that wants to make a smart investment in Mexico need to be sure they are drilling in the right area to obtain viable economic returns.

Figure 71: Location of the two possible shale supply chain hubs in northeast and east Mexico.

Upstream			
Bidding process and surface rights	**Exploration and appraisal**	**Site construction and development**	**Production and workovers**
<u>General activities:</u> • Geological information gathering • Data room and bidding process • Submission of E&P plan • Negotiation process with landowners (ejidatarios or private landowners) (180-210 days). • Water permits • Meet environmental and industrial regulations	<u>General activities:</u> • Seismic acquisition • Processing and interpretation of geophysical, and geological data • Engineering and economic data • Front end Engineering and • design (FEED) • Define exploration drilling locations • Access to drilling locations • Drilling, production testing and reserve estimates. • Determine number of wells	<u>General activities:</u> • Design specific well pad requirements. • Mobilize drill rig and equipment • Install infrastructure • Source and receive drilling mud additives • Mobilize fracturing equipment and fluids • Drilling • Install permanent well head • Treat and transport drilling waste and waste water (onsite treatment or transport to disposal wells)	<u>General activities:</u> • Install surface facilities • Install piping infrastructure • Well workover, intervention and stimulation • Land and roads reclamation
<u>Key activities:</u> • Exploration • Drilling	• Water management • Production	• Health, safety and environment (HSE) • Logistics and transportation	• Portfolio and risk analysis
<u>Participants:</u> • National and international companies • Federal and local authorities • Law firms	<u>Participants:</u> • National and international operators companies • Service companies • Construction companies (roads and pipelines) • Federal and local authorities • Law firms • Transportation companies • Commercial and industrial machinery and equipment rental and leasing • Environmental mediation services and advisors		
	<u>Key inputs and supplies:</u> • Freshwater sources • Proppant • Rigs • Power Systems • Pumping equipment • Gas compression equipment • Pipeline trenching and boring equipment • Measurement and control equipment • Storage tanks and equipment		
<u>Regulators:</u> **CNH, SENER, SHCP, ASEA, SEDATU**	**<u>Regulators:</u>** **CNH, ASEA, SHCP**		

Table 16A: Mexican shale supply chain general and key activities strategies, participants, key inputs and supplies, and regulators (upstream) (based on SARIG, 2012; Ernst & Young, 2014; Amion Consulting, 2015; and the Mexican Hydrocarbon Law).

<table>
<tr><th colspan="2">Midstream</th><th colspan="2">Downstream</th></tr>
<tr><th colspan="2">Gathering, transportation and natural gas processing</th><th>Refining and NGL fractionation</th><th>Storage, distribution and marketing</th></tr>
<tr><td colspan="2"><u>General activities:</u>
• Oil and gas separation
• Oil and gas metering
• Natural gas gathering and transportation through pipelines
• Natural gas processing
  • Dry gas, NGL
• Crude oil gathering and transportation through pipelines, trucks or railcars</td><td><u>General activities:</u>
• NGL fractionation
  • LPG, ethane, naphtha
• Crude oil refining (petroleum products)
  • LPG, naphtha, gasoline, kerosene, diesel, fuel oil, bitumen</td><td><u>General activities:</u>
• Dry gas storage and distribution for end user
  • Petrochemicals, power plants, petroleum industry, industrial and manufacturing, residential,
• LPG storage and distribution
  • Residential, transportation, industry and manufacturing
• Petroleum storage and distribution for end users
  • Industry and manufacturing, transportation, power plants</td></tr>
<tr><td colspan="4"><u>Key activities:</u>
• Pipeline construction
• Distribution and logistics
• Construction
• Marketing
• Refineries, processing centers
• Planning and inventory management</td></tr>
<tr><td colspan="4"><u>Participants:</u>
• National and international companies
• Federal and local authorities
• Environmental mediation services and advisors
• Pipeline management, control and safety
• Refineries and petrochemical</td></tr>
<tr><td colspan="4"><u>Key inputs and supplies</u>
• Pipelines
• Trucks
• Processing centers
• Supply terminals
• Compression stations</td></tr>
<tr><td colspan="2"><u>Regulators:</u>
SENER, CENAGAS, ASEA, CRE</td><td><u>Regulators:</u>
SENER, ASEA, CRE</td><td><u>Regulators:</u>
SENER, ASEA, CRE</td></tr>
</table>

Table 16B: Mexican shale supply chain general and key activities strategies, participants, key inputs and supplies, and regulators (midstream and downstream) (based on SARIG, 2012; Ernst & Young, 2014; Amion Consulting, 2015; and the Mexican Hydrocarbon Law).

Agency	Main Activities
Department of Energy (SENER)	Develops Mexico's upstream policy; determines areas to be made available and the schedule for public bidding; chooses that of the contract models to apply to which contract; and approves the non-fiscal terms of the contract.
Department of Finance (SHCP)	Determines the fiscal terms to apply to each contract and participates in audits.
National Hydrocarbon Commission (CNH)	Interfaces with PEMEX and private companies, conducts and manages contracts, and oversees the industry.
National Agency for Industrial Safety and Environmental Protection (ASEA)	Regulates environmental and safety concerns.
Energy Regulatory Commission (CRE)	Grant permits for transportation, storage, distribution, compression, liquefaction, decompression, regasification, marketing, and sale of crude oil, oil products, and natural gas.
National Natural Gas Control Center (CENAGAS)	Manages system for gas distribution and storage.

Table 17: Main activities of the Mexican Regulatory Agencies (Ribando Seelke et al., 2015).

Chapter 7. Conclusions

Mexico's oil and gas production has been steadily declining, with a reserves-to-production ratio for proved reserves of 10 years at the time of writing. PEMEX has struggled to invest in its deepwater exploration and production projects as well as onshore resources, including shale. As such, Mexico initiated a groundbreaking reform process in order to attract private capital into the development of its conventional and unconventional resources since the nationalization of the industry in 1938. The Eagle Ford Group in Texas has had an amazing development in the last 7 years. This success in addition to the fact that the U.S. is the home of numerous shale plays has led to speculate about the possibility of replicating this success in other parts in the world, including Mexico. Specifically, the shale resources of the Mexican equivalent formations to the Eagle Ford Group in Texas.

The geological screening of the Texas Gulf Coast and east and northeast Mexico indicates that their distinct paleogeographic and tectonic development preclude a straightforward correlation between the Eagle Ford Group of Texas and equivalent formations in Mexico:

1- In Texas, east of the Frio River Line, where Eagle Ford sweet spots prevail, extensional tectonics prevailed during the Mesozoic-Cenozoic while in northeast and east Mexico compressional tectonics influenced sedimentation from the late Cenomanian through the Eocene.

2- In Mexico, the late Cenomanian compression led to paleobathymetry variations that may have influenced the lithology, distribution, and thickness of the lower organic-rich interval of the Eagle Ford Group and the Agua Nueva Formation. The late Cenomanian compression produced the uplift of a western landmass that was a source of detrital argillaceous sediments mainly into the Indidura Formation leading to poor preservation of organic matter. The Laramide orogeny produced the exhumation of the late Cenomanian-Turonian section in a great part of Mexico, and its burial in foreland basins below Cenozoic sediments with contrasting thickness.

3- In Mexico, as in the U.S., the understanding of depth-dependent factors such as thermal maturation, pore pressure, and viscosity are critical for the assessment of sweet spots.

4- The first candidates to be focus areas are those regions that received little argillaceous material during the late Cenomanian-Turonian and remained buried at adequate depths between maturation of organic matter and preservation of pore pressure. The geological screening in this work resulted in four areas with the potential to be sweet spots: the Sabinas Coal Basin, a northwest-southeast trending swath along the western part of the Burgos Basin, the southwestern part of the Maverick Basin, and the southwestern part of the Tampico-Misantla Basin. However, substantial uncertainty exists about the expected recoverable hydrocarbons and the potential future development of the Eagle Ford Group in east and northeast Mexico.

The inconsistency of the results of the first eight wells drilled in the Eagle Ford of Mexico generates uncertainty about the commerciality of this formation. If Mexico wants to replicate the success of Texas, a better understanding of the geology needs to be developed by drilling more wells in areas that are most promising on the basis of available geologic data.

However, a better understanding of geology is not a guarantor of success in developing Mexico's shale resources. Non-geologic factors are also very important. The focus areas (La Huasteca and Northeastern Mexico) present specific and serious technical and operational challenges for companies such as:

1- Water shortage or mismanagement of water resources,

2- Insufficient road infrastructure,

3- Ability to deal and negotiate with people with strong cultural and social roots.

The new law provides compensation for the landowners, a process to negotiate with the companies, and states that the energy sector activities have priority over any other economic activity. These foundations are an opportunity to maintain, and, if necessary, enhance the quality of life of the communities with tangible benefits through the support of other economic activities encouraging the human capital development of Mexico. However, the new law has raised concerns among civil, environmental groups, landowners, and indigenous communities about the impacts of the Energy Reform. Oil companies will have the challenge of exploring ways to avoid disturbing the environment and social fabric by reinforcing confidence and by sharing information about the whole exploration and production process. If the understating of the geology and the geotechnical factors allows identification of sweet spots in the proposed focus areas, the geographic and socio-economic conditions of the northern region will permit a faster development. However, the La Huasteca region will represent a bigger challenge since the Agrarian Cores occupy a greater area, and its cultural background includes examples of resistance to major industrial or infrastructure projects, including oil and gas operations.

Infrastructure will be another challenge. At this time, it is not possible to predict where the most productive locations will be, or the fluid composition of production (e.g., amount of natural gas liquids). Nevertheless, the existing midstream infrastructure (natural gas pipelines, processing and fractionation facilities, liquids pipelines and midstream and downstream facilities needed to monetize the resources) will not be sufficient in the case of success. As some researchers suggested, an optimization modeling approach can be pursued to develop these facilities in a timely and cost-effective manner to facilitate most efficient development of upstream assets. However, more infrastructure will be built as the new fields are developed; still, proactive infrastructure planning might help move things forward faster, especially given the need to ensure local community support for these projects.

A possible strategy that might take advantage of existing infrastructure could comprise of a Northeastern Hub embracing the Burgos, Maverick, and Sabinas Coal Basins, and an Eastern Hub, including the Tampico-Misantla Basin. In any case, high-quality project management and decision-making process based on economic and scientific data, awareness of local community needs, transparency by all participants, and the integration of research centers are crucial for success.

The geological screening to the Eagle Ford Group and equivalent formations, and the review of the status of the non-geologic factors permit to say that shale industry in Mexico could be developed if the companies overcome the technical, infrastructure, social and cultural challenges. However, first and foremost, geology should permit commercially viable production in sufficiently large area to support the development of a supply chain as discussed in this thesis. At the time of writing, the results from the first eight wells are mixed at best, an unfavorable low oil and gas price scenario has impacted the industry, and local challenges can be significant in at least some locations. As such, it is probable that unconventional resources of the Mexican part of the Eagle Ford will have to wait for better times.

Glossary[5]

- Anticline - A fold, generally convex upward, whose core contains the stratigraphically older rocks.
- Argillaceous - Pertaining to, largely composed of, or containing clay-size particles or clay minerals, such as an "argillaceous ore" in which the gangue is mainly clay; esp. said of a sediment (such as marl) or a sedimentary rock (such as shale) containing an appreciable amount of clay.
- API gravity - A standard adopted by the American Petroleum Institute for expressing the specific weight of oils.
- Bathymetry - The measurement of ocean depths and the charting of the topography of the ocean floor.
- Bituminous - A sedimentary rock that is naturally impregnated with, contains, or constitutes the source of bitumen.
- Clastic sediment - A sediment formed by the accumulation of fragments derived from preexisting rocks or minerals and transported as separate particles to their places of deposition by mechanical agents (such as water, wind, ice, and gravity).
- Diagenesis – Diagenesis is a process through which the system tends to approach equilibrium under conditions of shallow burial, and through which the sediment normally becomes consolidates. The depth interval concerned is in the order of a few hundred meters. In rare cases it may reach 2,000 m. In the diagenetic interval, the increase of temperature and pressure is small, and transformations occur under mild conditions (Tissot and Welte, 1978).

[5] Unless otherwise stated the definitions are taken from the American Geological Institute, 2005.

- Dolomite - A carbonate sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite, or a variety of limestone or marble rich in magnesium carbonate.
- Eustasy - Refers to global sea level independent of local factors; namely the position of the sea surface with reference to a fixed datum including the center of the earth or a satellite in fixed orbit around the earth (SEPM, 2015).
- Facies - The aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin; esp. as differentiating the unit from adjacent or associated units.
- Facies Change - A lateral or vertical variation in the lithologic or paleontologic characteristics of contemporaneous sedimentary deposits. It is caused by, or reflects, a change in the depositional environment.
- Foldbelt - A belt of folds whose hinges are roughly parallel to one another. In general, the folds involved are the product of a single deformation event.
- Foreland basin - A linear sedimentary basin in a foreland [tect]. These basins subside in response to flexural loading of the lithosphere by thrust sheets.
- Graben - An elongate trough or basin, bounded on both sides by high-angle normal faults that dip toward one another
- Half graben - An elongate, asymmetric trough or basin bounded on one side by a normal fault.
- Homocline - A general term for a series of rock strata having the same dip.
- Horst - An elongate block that is bounded on both sides by normal faults that dip away from one another.
- Kerogen - Fossilized insoluble organic material found in sedimentary rocks, usually shales, which can be converted to petroleum products by distillation.

- Lithofacies - A lateral, mappable subdivision of a designated stratigraphic unit, distinguished from adjacent subdivisions on the basis of lithology, including all mineralogic and petrographic characters and those paleontologic characters that influence the appearance, composition, or texture of the rock; a facies characterized by particular lithologic features.
- Lithology - The definition of rocks, esp. in hand specimen and in outcrop, on the basis of such characteristics as color, mineralogic composition, and grain size.
- Monocline - A local steepening in an otherwise uniform gentle dip.
- Permeability - The property or capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure and is a function only of the medium.
- Porosity - The percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected.
- Pressure gradient - The rate of variation of pressure in a given direction in space at a fixed time.
- Orogeny - Literally, the process of formation of mountains.
- Thermal maturation - A rock or petroleum that has been exposed to high temperatures resulting in a different distribution of compounds.
- Trace element - An element that is not essential in a mineral but that is found in small quantities in its structure or adsorbed on its surfaces. Although not quantitatively defined, it is conventionally assumed to constitute significantly less than 1.0% of the mineral.
- Relict [geomorph] - A topographic feature that remains after other parts of the feature have been removed or have disappeared.
- Siliciclastic - Pertaining to clastic non-carbonate rocks.

- Sorption - The general process by which solutes, ions, and colloids become attached to solid matter in a porous medium.
- Stress - In a solid, the force per unit area, acting on any surface within it, and variously expressed as pounds or tons per square inch, or dynes or kilograms per square centimeter.
- Subsidence - The gradual downward settling of an area of the earth crust with respect to surrounding areas (Biddle and Christie-Blick, 1985). Subsidence of the crust to form sedimentary basins is induced by the following processes (Dickinson, 1974, 1976 in Ingersoll, 1988): (1) attenuation of crust due to stretching and erosion; (2) contraction of lithosphere during cooling; and (3) depression of both crust and lithosphere by sedimentary or tectonic loads, which are isostatically compensated either locally or regionally (Ingersoll, 1988).
- Viscosity - The property of a substance to offer internal resistance to flow.

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